MODELLING ALIEN VEGETATION INVASIONS AND CLEARING STRATEGIES

LUCILLE SCHONEGEVEL B.SC.
STUDENT NUMBER: 13257897

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SUPERVISOR: MR A. VAN NIEKERK
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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my original work and has not previously in its entirety or in part been submitted at any other university for a degree.

SUMMARY

The burgeoning problem of alien plant invasions in South Africa necessitates effective decision-making based on an understanding of the complex processes that govern these invasions. Due to the spatial nature of the problem, this study explored the use of Geographic Information Systems and spatial models for predicting the spread of alien vegetation and assessing the effectiveness of clearing strategies. The Spatially Explicit Individual Based Simulation (SEIBS) model was identified as a potentially useful tool for alien plant management. This thesis documents the further investigation and development that was necessary before recommendations could be made regarding the future use of the model.

The landscape version of the SEIBS model was adapted to allow for the convenient input and output of spatial data, making it possible to simulate invasions in different areas. An ArcView extension was developed in order to facilitate the pre- and post-processing of the spatial data required and created by the model. Changes were also made to the fire routine of the model. The new version of the model was called Clear.

A series of model tests for *Pinus pinaster* were conducted to assess the sensitivity of the Clear model to spatial resolution, initial spatial fragmentation and heterogeneity. These tests revealed that the model was sensitive to changes in resolution and needed to be reparameterised when using different resolutions. The initial level of fragmentation was shown to have a major influence on the invasion rate. Although greater levels of spatial heterogeneity with respect to vegetation age did not significantly affect the spread rate, it did increase the effectiveness of clearing strategies based on clearing juvenile or sparse vegetation.

Based on these tests, it is concluded that the model can be readily applied to different areas, provided the influence of spatial characteristics is understood and accommodated. The Clear model was shown to be a useful tool for evaluating clearing strategies and for investigating invasion rates. It is recommended that the model be introduced to a wider audience, in order to obtain user feedback and further improve the accessibility of the model.

Key words: alien invasive plants, spatial modelling, management

OPSOMMING

Die toenemende probleem van uitheemse indringerplante in Suid Afrika, noodsaak effektiewe besluitneming wat gebaseer is op 'n begrip van die ingewikkelde prosesse wat indringing beheer. As gevolg van die ruimtelike geaardheid van die probleem, is die gebruik van Geografiese Inligtingstelsels en ruimtelike modelle vir die voorspelling van die verspreiding van indringerplante en die evaluasie van die effektiwiteit van opruimingstrategieë in hierdie studie ondersoek. Die *Spatially Explicit Individual Based Simulation* (SEIBS) model is as 'n moontlike geskikte hulpmiddel vir die bestuur van uitheemse indringerplante geïdentifiseer, alhoewel verdere ondersoeke en ontwikkeling nodig was voordat aanbevelings vir die gebruik van die model gemaak kon word.

Vir hierdie studie is die landskapweergawe van die SEIBS model aangepas om die maklike toevoer en afvoer van ruimtelike data te fasiliteer. 'n ArcView uitbreiding is ontwikkel om met die voor- en naprosessering van ruimtelike data, wat deur die model gebruik en geskep is, te fasiliteer. Veranderinge is ook aan die vuur sub-roetine van die module gemaak. Die nuwe weergawe van die model word Clear genoem.

'n Reeks toetse is vir *Pinus pinaster* gedoen om die sensitiwiteit van die Clear model te toets teenoor ruimtelike resolusie, aanvanklike vlak van versnippering en vlak van heterogeniteit. Vanuit die toetse het dit geblyk dat die model sensitief was ten opsigte van verandering in resolusie en dat die model se parameters verstel moes word wanneer verskillende resolusies gebruik word. Daar is ook gewys dat die die vlak van aanvanklike versnippering 'n groot impak op die verspreidingstempo het. Alhoewel hoër vlakke van ruimtelike heterogeniteit teenoor plantegroei nie 'n merkbare impak op die verspreidingstempo gehad het nie, het dit wel die effektiwiteit van opruiming-strategieë, gebaseer op die opruiming van jong of yl verspreide plante, verbeter.

Die gevolgtrekking wat uit die toetse gemaak kan word is dat die model geredelik op verskillende areas toegepas kan word, op die voorwaarde dat die invloed van ruimtelike eienskappe in ag geneem word en in berekening gebring word. Dit word aanbeveel dat die model wyer bekendgestel word om sodoende gebruikersterugvoer te bekom.

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CHAPTER 1:
RESOURCE PLANNING IN A DYNAMIC ENVIRONMENT

Water is fast becoming a scarce resource for South Africa's growing population. In order to manage water in a more effective and equitable manner, Parliament recently passed the National Water Act (No. 36 of 1998). This Act gave rise to the current initiatives to draw up catchment management plans, which include plans to clear invasive alien vegetation. The Working for Water (WfW) programme, whose primary function is to implement alien vegetation clearing plans, is the world's most comprehensive initiative to clear alien plants (Versfeld, Le Maitre & Chapman 1998).

The major problems associated with invasive alien plants include a reduction in steam flow, local extinction of indigenous plant species and altered fire behaviour (Van Wilgen & Richardson 1985, Richardson & Cowling 1994). To better understand these problems, a great deal of research is being conducted on topics relating to the impacts and control of alien invasive vegetation. Many long-term experiments have been carried out and a wide range of local as well as international literature is available. It is estimated that approximately 750 000 hectares will need to be cleared each year to win the battle over a 20-year period. The former minister of Water Affairs and Forestry, Professor Kadar Asmal, wrote that in spite of all the knowledge gathered and commitment shown to clearing alien vegetation, achieving this goal would still require a great deal of innovative action (Versfeld, Le Maitre & Chapman 1998). It is the author's hope that this study will play a small part in facilitating the innovative action required.

1.1 RESEARCH PROBLEM

The control of invasive plants involves an ongoing battle between clearing strategies and ecological responses to the forces of nature. Making decisions about which clearing strategy to follow is thus no trivial matter. Choosing an inefficient strategy can result in the loss of valuable resources and therefore decisions must be based on the best possible understanding of the area and the factors influencing the spread of the invasive plants. Decision Support Systems (DSS) have therefore been developed in order to provide this information to the WfW programme (Schonegevel 2000). The importance of the spatial component was recognised early in the process of developing decision support tools for the WfW programme, and their current tools are consequently based on the ArcView and ArcInfo platforms (Geographic Information Management Systems 1998).

From the literature it is clear that in order to predict and understand the spread of alien vegetation, the spatial and temporal variability of resources such as fire and open space need to be taken into account (Van Wilgen, Richardson & Higgins 2000; Schonegevel 2000). The spatial analysis performed by the WfW programme's Alien Catchment Management System (ACMS) and Project Information System allows for a good understanding of the past and current environment and is useful for monitoring and budgeting purposes. However, these static modelling systems do not allow decision makers to understand the dynamic processes involved in alien vegetation spread and clearing.

Expert knowledge based on years of scientific investigation and empirical studies can be incorporated into models. Although a number of alien spread models have been developed, they have not yet been successfully adopted as decision support tools. If a model is to become more than a research project it must be easy to use and its capabilities and limitations must be clearly understood. The Clear model described in Chapter Four was identified as a potentially useful decision-making tool, however its capabilities and limitations required further investigation.

1.2 RESEARCH METHODOLOGY

A wide-ranging literature survey was conducted to provide insight into a broad range of issues pertaining to the impact and management of alien invasive plants in the South African and Western Cape context. A more focussed investigation into DSS and spatial models for alien vegetation management was conducted by means of discussions with experts and the review of journal articles, instruction manuals, data specification documents and Internet sites. While articles that focus on area specific characteristics and physiological aspects of plants are plentiful, few attempts at modelling alien plant spread are reported in the literature (Higgins 1998). The literature survey indicated that the suite of models developed by Higgins showed the potential to greatly increase the understanding of the dynamic processes involved in alien vegetation spread and clearing, and in so doing, lead to more cost effective clearing strategies.

However, none of the models developed by Higgins were ready for wider use. Therefore, this study included the development of a more accessible version which incorporated all the necessary features to enable users to input spatial data. The modified version has been called Clear for the sake of brevity. This study has also addressed the issue of model accessibility through the development of an ArcView extension. The ArcView extension facilitates the processing of spatial information to be used as input for the model and allows the model output to be imported into a suitable format for further analysis. In this report an attempt has been made to document the functionality of the model as far as possible in an instructive manner. However, the writing of a detailed user manual goes beyond the scope of this thesis.

The validation of the Spatially Explicit Individual Based Simulation (SEIBS), model from which the Clear model was derived, is described in Higgins, Richardson, Cowling & Trinder-Smith (1999) and Higgins, Richardson & Cowling (1999b). These previous validation exercises did not include a sensitivity analysis of the key spatial aspects that become relevant when applying the model in situations that differ in scale and configuration. Therefore, a series of model tests was designed and executed to investigate these aspects. Comparing the results of the different scenarios provided further insight into the influence of different fire regimes, spatial resolutions and spatial configurations on the invasion process. The insights gained in dealing with these issues provided the basis for recommendations for future use of the model.

1.3 STRUCTURE OF THIS THESIS

The following chapter of this thesis provides the context for the study in that it highlights the need for effective management. The role of DSS and spatial models is then discussed in Chapter Three. Chapter Four describes the data requirements, user-interface and processes modelled. The series of model tests mentioned above is described in Chapter Five. The development and use of an ArcView extension for facilitating the pre- and post-processing of spatial data is described in Chapter Six. The report concludes with a discussion of the results and recommendations for future research.

CHAPTER 2: ALIEN INVASIVE VEGETATION

Many plant species have been introduced to South Africa for a variety of reasons including forestry, dune stabilisation, windbreaks, shade and the creation of more aesthetic surroundings. These plants are known as aliens. Many of these aliens have invasive properties and where their spread has remained unchecked, invasion has taken place on a regional scale (Moll & Trinder-Smith 1992). Invading alien plants have covered 10 million hectares (8% of South Africa) and are expected to continue invading, doubling their impact every fifteen years if left unchecked (Versfeld, Le Maitre & Chapman 1998).

More than 900 alien plant species occur in South Africa. Some of these play an important role in feeding people and livestock, as well as providing fuel and raw material for industry. Of these alien species, 198 are listed as invasive in the new regulations promulgated under the Conservation of Agricultural Resources Act (Regulation R7032 of 2001).

The degree to which alien vegetation becomes invasive is determined by several factors:

- The suitability of the area in terms of soil type, rainfall, temperature, altitude and slope;
- The fecundity, reproductive age and seed dispersal methods of the alien plant;
- Landscape disturbance such as fires and erosion; and
- Competitiveness of existing vegetation.

The Western Cape is the most heavily invaded province, especially the wetter catchments of the coastal mountain ranges and the broad coastal lowlands. The most important invader species are *Acacia Cyclops* (Rooikrans), *Acacia saligna* (Port Jackson Willow), *Acacia mearnsii* (Black Wattle), *Hakea sericea* (Silky Hacea) and *Pinus pinaster* (Cluster Pine). Pines were originally introduced from Europe, while the *acacia* and *hakea* species were introduced from Australia. The plants were introduced to augment the value of the Cape's natural resources and indeed some species still support whole industries. However, the negative impacts of these invaders is now becoming more prominent and there is an urgent need to protect our natural resources from these impacts.

2.1 IMPACTS OF ALIEN INVASIVE PLANTS

Dense stands of pines and other invasive trees and shrubs pose serious problems for catchment management (Richardson & Cowling 1994). Major problems associated with these invasions include a reduction in stream flow (Versfeld & van Wilgen 1986), local extinction of indigenous plant species (Richardson, Macdonald & Forsyth 1989) and altered fire behaviour (Van Wilgen & Richardson 1985). These impacts are described in more detail below.

The national alien plant clearing campaign is called Working for Water due to the effect that alien plants have on stream flows. In the Western Cape the invasion of fynbos by woody species has resulted in an increase in transpiration and evaporation of intercepted rainfall (Le Maitre, Van Wilgen & Chapman 1996). The water is taken up and used by the alien plants, rather than reaching the rivers through run-off or soaking down to the water table. Based on long-term monitoring studies in the Western Cape, it is estimated that the stream flows in catchments containing alien plants are reduced by between 30 and 50%. On a national scale the loss of water due to alien plants is 7% of the annual flow in South Africa's rivers (Versfeld, Le Maitre & Chapman 1998).

Due to their more efficient reproduction and spreading, invasive plants suppress the growth of indigenous plants, resulting in the elimination of indigenous plant species in the area. The Cape flora consists of 8574 species, 62% of which are endemic. The impact of alien plants on biodiversity is potentially enormous, as alien species have been found to reduce native plant species richness by 50-86% in densely invaded areas (Richardson, Macdonald & Forsyth 1989).

Fuel loads at invaded sites can be increased by up to ten fold. This increases the fire intensity and causes physical and chemical soil damage, increased soil erosion and decreased germination from indigenous seed banks (Van Wilgen, Richardson & Higgins 2000). The most successful taxa in the pine and hakea genera share a suite of life history attributes that facilitate rapid migration and explosive population growth in a fire-prone environment (Richardson 1989). These invaders have large numbers of small seeds which accumulate between fires. The adult plants are often killed by fire but the short juvenile period of the plants ensures a dense population and larger seed bank before the next fire. Dense stands of alien plants provide a greater fuel load resulting in more intense fires. These intense fires may destroy, rather than stimulate fynbos seeds (Richardson 1989), while the fire resistant seed storage structures of the invader plants give them a reproductive advantage (Richardson & Brown 1986). Therefore, although fynbos depends on fire as a method of seed dispersal and plant renewal, the alien species also take advantage of fires to invade new areas and are often better suited to the altered fire behaviour that they induce.

2.2 MOTIVATION FOR MANAGEMENT

Alien invasive vegetation is recognised as a national problem and legislation exists to control their spread. The Conservation of Agricultural Resources Act (No. 43 of 1983) provides directions for the control of alien plants (Ferraz 2000). Regulation 15 of this act is currently being revised to further strengthen the legal standing of the act. Alien invasive legislation is also being considered as part of the new Biodiversity Act for South Africa (Botha 2001).

Legislation alone is not enough to control the spread of alien vegetation and thus the management of alien invasive vegetation receives substantial government support and funding. Since 1995 the expenditure on plant clearing has exceeded R100 million per year, with potential future spending being as much as R600 million per year (Versfeld, Le Maitre & Chapman 1998). Expenditure for WfW exceeded R300 million for the period April 2000 to March 2001 (Working for Water 2001). Sinclair (1996) identified water and biodiversity conservation as well as political and economical considerations, as the four key driving forces behind alien control and the creation of relevant legislation. These driving forces are interrelated, but are each worthy of individual mention and are discussed below.

The first motivating factor is the need to conserve water, as it is fast becoming a scarce resource for South Africa's growing population. The reduction of stream flow due to riparian invaders is a deep concern. It is likely that the impacts will be most severe for rural communities who depend on river flow for water access, due to the lack of infrastructure needed to store and supply water. The agricultural and industrial sectors, as well as individual water users, are already experiencing the effects of increased water tariffs.

In the past, the solution to water shortages has been the construction of new dams. However, this will prove to be ineffective if the spread of alien vegetation into catchment areas is not curtailed. The cost of the water that will be saved during the 20-year Working for Water programme has been calculated to be in the order of 45 cents per cubic meter (Versfeld, Le Maitre & Chapman 1998). When compared to the cost of continuously building new dams, the cost of clearing aliens compares favourably.

The second key reason for alien management is the need to conserve biodiversity. The natural fynbos vegetation of the Western Cape is valuable due to its high number of endemic species and genetic storage value (Higgins, Turpie, Costanza, Cowling, Le Maitre, Marais & Midgley 1997). The plant biodiversity of an area affects the insect and animal diversity, which in turn has existence value as well as direct use value. Although most governments promote biodiversity conservation, the general public often fail to recognise the importance of such action (Sinclair 1996). South Africa is a signatory of the Convention on Biodiversity (1992) and is thus obliged to prevent, control or eradicate alien species that threaten ecosystems, habitats or species.

Both water and biodiversity conservation are closely linked to the third motivating factor – economics. The economic benefits of having an area covered by fynbos rather than by woody invasive plants have been identified as:

- Low water use;
- Wildflower harvest potential;
- Attractiveness to hikers and eco-tourists;
- Less intense veld fires which require less control; and
- Protection of valuable soil from fire damage and erosion.

Lastly, political factors are also an important consideration. Public support for government action commonly hinges around a perception of material gain. Consequently, the political decisions needed to provide funds for alien control will be influenced by the need of the government to create jobs, distribute benefit to particular regions and undertake high profile activities. The Working for Water Programme is one of the most successful projects resulting from the Reconstruction and Development Programme in South Africa. Initially, it provided employment to about 50 000 people (Versfeld, Le Maitre & Chapman 1998), while currently it provides employment to 23 000 people (Working for Water 2001). The programme also creates secondary industry opportunities through the wood, water, productive land and trained people that it generates. A good example of such a secondary industry is the rustic furniture and crafts product that are made from wood of invasive alien plants. Through providing employment and the development of secondary industries, WfW enhances the quality of life in the most marginalized sectors of South Africa.

2.3 MANAGEMENT STRATEGIES FOR ALIEN INVASIVE VEGETATION

As the problem of alien invasive plants is enormous, a long-term approach has been adopted for their clearing. Areas to be cleared have to be prioritised according to the impact on natural resources and the potential for spreading to non-invaded areas. The order of work is important and the following issues need to be carefully considered:

- It is important to clear the aliens in a manner that reduces the risk of cleared areas being re-invaded by other invaded areas. For example, upstream areas should be cleared before downstream areas if the river transports the seeds.
- A balance needs to be maintained between clearing new areas and follow-up operations on previously cleared areas.

- Prevention is cheaper than clearing and therefore un-invaded areas must be protected from invasion.
- The economic benefits of clearing areas with high tourism, biodiversity, productivity or water yield potential are necessary to maintain the support for the continuation of the clearing project. Therefore management strategies need to be supported by well developed models which not only model the cost, but also the benefits of clearing.

An integrated approach involving the combined use of a range of methods is usually necessary to control invasive alien plants effectively. The nature of the integrated approach for control will depend on the invading species, the availability of resources and other area specific factors (Van Wilgen, Richardson & Higgins 2000). The following methods are available for the control of alien invasive plants:

- Mechanical methods;
- Chemical methods; and
- Biological control.

Mechanical methods involve felling or uprooting of plants and their removal from the site. Fire can be used to germinate the remaining alien seeds after mechanical clearing, so that the seedlings can be hand weeded in a follow up operation. Mechanical control is labour-intensive and thus expensive (Ferraz 2000).

Herbicides can be applied to prevent sprouting of felled trees and to kill seedlings. Although new herbicides tend to be less toxic, concerns over the environmental impacts still remain. Their use is therefore governed by legislation and the effective and safe use requires a high level of training.

By introducing biological control in the form of the plant's natural enemies, invasive plants can become naturalised aliens. These biological controls take the form of species-specific insects and diseases from the alien plant's country of origin. Concerns remain regarding possible impacts on non-target plants and invasive plants with commercial value.

Mechanical and chemical control forms an important part of short-term strategies. In the medium term, rigorous follow-up and rehabilitation is required. However the cleared area will always remain susceptible to another invasion and thus biological control is the only long-term solution. Biological controls have already been successfully introduced for *Hakea aericea*, *Acacia longifolia* and *Acacia saligna* (Versfeld, Le Maitre & Chapman 1998).

CHAPTER 3:
USE OF DECISION SUPPORT SYSTEMS AND SPATIAL MODELS

Unplanned fires, floods or budget cuts can wreak havoc with a carefully planned control programme and must be accommodated for in a flexible, adaptive approach (Van Wilgen, Richardson & Higgins 2000). This section describes how decision support systems and spatial modelling can play a role in planning control programmes and allowing managers to visualise the effects of events such as fires or changes in budget.

3.1 DECISION SUPPORT SYSTEMS AND ALIEN INVASIVE VEGETATION MANAGEMENT

The burgeoning scope of South Africa's nation-wide alien clearing programme makes effective information management crucially important. The increasing use of computers has resulted in information that was previously captured on paper maps or reports being entered into computer systems. The development of DSS, which could to a greater or lesser extent process and interpret the information, is a logical next step. The WfW programme recognised the spatial nature of the alien spread problem and have funded the development of a spatial database, a Project Information System and an Alien Catchment Management System.

The WfW programme database runs on an ArcStorm database engine and stores alien vegetation coverages together with related attribute tables. The Project Information System makes use of the data in the database and is designed to manage the daily/weekly project level data as well as generate monthly reports for provincial project leaders and summary reports for programme management at a national level (Geographic Information Management Systems 1998). The Project Information System is concerned with recording the current situation, documenting progress made and the budgeting of individual projects. Therefore it is not concerned with calculating the spread of alien vegetation. The Alien Catchment Management System (ACMS) was developed by the CSIR and designed to allow managers to strategically plan for the long-term removal of alien vegetation in a catchment area (Muller 2000). The ACMS is a coarse tool for long term strategising. ACMS includes a spread model which operates on spatial data, but is not a spatial model. The areas of invaded polygons and potentially invadible polygons are used together with logarithmic and exponential functions to predict the size of the invaded area at a future date. The vector-based approach to spatial modelling was a significant simplification and the developers felt that a cell-based model would be more desirable (Muller 2000). The cost of acquiring the Spatial Analyst software was a major factor in deciding against a cell-based modelling approach. A number of international attempts as well as two South African attempts have been made to produce cellular automated models. The various approaches to alien spread modelling are discussed in the next section.

3.2 ALIEN SPREAD MODELLING

Certain attributes of the life history or eco-physiology of the plant enable it to compete successfully in a new environment. In fire prone fynbos the short juvenile periods, large and serotinous seed banks and highly dispersible seeds facilitate rapid invasion. The spatial and temporal variability of resources such as nutrients, moisture and space also influence the pattern of an invasion. Space is made available through disturbances such as fire that at the same time facilitate the spread and germination of seeds. Furthermore, the interaction of alien plants with their new environment is an important aspect that influences the variables and parameters of plant spread models.

Different models have different procedures for abstracting these interactions into input parameters that allow for the estimation of alien abundance. Invasion is characterised by two important processes: expansion (spread) via dispersal, which results in an increase in the total area invaded; and an ongoing increase in the density of the invading species. Higgins and Richardson (1996) developed a conceptual model of alien plant spread (Figure 3.1), which illustrates the relationship between the main components of alien plant invasions. The conceptual model includes a feedback effect of alien abundance on resource availability (Higgins & Richardson 1996). An example of such a feedback loop is when an increase in density of alien vegetation increases the number of seeds available for dispersal, but reduces the space available for recruitment.

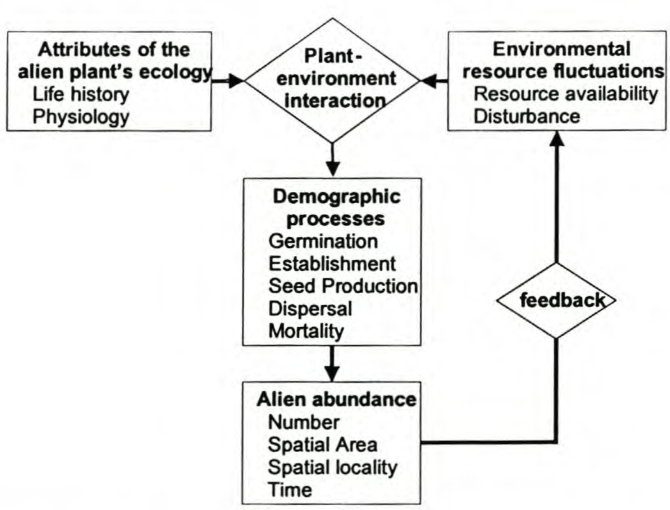


Figure 3.1: A conceptual model for alien plant spread (adapted from Higgins & Richardson 1996).

Numerous models exist for simulating population spread. These are categorised by Higgins & Richardson (1996) into three types:

- Simple-demographic;
- Spatial-phenomenological; and
- Spatial-mechanistic.

Simple-demographic models predict future population sizes based on assumptions about population growth and estimated demographic parameters. These models are appropriate where the growth rate of a population is primarily dependant on the reproductive rate.

Spatial-phenomenological models predict invaded area as a function of time. Invasion rates are based on historical data and not on ecological processes. These models do not enhance our understanding of the ecological process that we need to manage in order to control invasions and are only appropriate for use where sufficient historical data about the particular invasion is available.

Spatial mechanistic models are based on estimates of ecological parameters. The predictions are therefore a function of ecological interactions and the model's assumptions. Three subgroups of models can again be identified:

- Reaction-diffusion models;
- Individual based models; and
- Metapopulation models.

Reaction-diffusion models are unable to model the responses of alien plants to environmental heterogeneity and stochastic disturbances such as fire, whereas metapopulation and individual based models allow for the incorporation of stochastic events and spatial heterogeneity. Individual based models are needed where fine-scale ecological heterogeneity is important. Examples of individual based models are:

- SORTIE (Ribbens 1994); and
- SEIBS (Higgins, Richardson & Cowling 1996 and 1999b).

Metapopulation population models are popular as they aggregate individuals into populations and are thus less computationally demanding than individual based models. Examples of metapopulation models are:

- The INVADE model (Auld and Coote 1980);
- The CSIR's Alien model (Le Maitre 1995);
- The ECOTONE model (SLIK-ECO 2000); and

- The Spatially Explicit Landscape Extent Simulation model (SELES), which was derived from the SEIBS model (Higgins, Richardson and Cowling 1999a).

Factors that were considered when deciding on an approach to follow in this study were flexibility, ability to develop user interfaces, incorporation of recent scientific findings and applicability to the South African invasions. The CSIR's ArcInfo Alien model was attractive as it was integrated into a GIS. However, it was found to be inflexible due to the limited range of grid cell routines provided in ArcInfo Grid (Le Maitre 1995) and slow due to the fact that it was written using a scripting language. Developing a new model in ArcView would also not overcome these hurdles and thus the idea of developing the model within a GIS was abandoned. Section 3.3 explains this hurdle in further detail. SEIBS and SELES were developed over the past four years and thus incorporate the most recent scientific understanding. The flexible Delphi environment in which the SEIBS and SELES models were developed, and the work done in parameterising the model for South African conditions (Higgins, Richardson, Cowling & Trinder-Smith 1999), made them the most attractive choice for further investigation.

3.3 SPATIAL MODELLING OF ALIEN INVASIVE VEGETATION

The issues which natural resource management must address are increasing both in terms of complexity and breadth of spatial and temporal scale (Morain 1999). In order to predict the spread of alien vegetation and make decisions for its management, numerous time and spatially dependent factors need to be taken into account. To this end, GIS and spatial models have an important role to play, as they allow managers to visualise and assess the consequences of a variety of management strategies.

The spatial technologies that have emerged over the past 25 years enable managers to process massive amounts of data from different sources; and to visualise, model and predict outcomes of management scenarios. Although raster GIS offers many attractive features as a spatial modelling environment - such as data management, spatial analysis and visualisation - it has limitations in terms of speed and flexibility.

As a consequence of the historical emphasis on GIS as a spatial database management system, the results of each spatial operation are stored in the database. This process of storage and retrieval imposes severe performance penalties when modelling dynamic processes (Slothower RL, Schwartz PA & Johnston KM 1996). Current raster GIS technologies use procedures which process each cell in a grid sequentially. Each cell becomes the focus cell and calculations based on an appropriate neighbourhood are performed for the cell. This means that one can only model how a neighbourhood affects a cell and not how a cell affects a neighbourhood. This makes the implementation of long distance dispersal patterns extremely difficult. The two technological limitations mentioned above are likely to be overcome in the near future as contributions from the field of remote sensing are incorporated into GIS and as computing power continues to improve (Slothower, Schwartz & Johnston 1996).

In this study GIS is used as a pre- and post-processing tool for the spatial data required and created by the model. The model itself was developed independently of the GIS environment. Due to the limitations mentioned above, no attempt was made to develop a model within ArcInfo or ArcView. No other GIS environments were considered, as the added data exchange complications, training requirements and financial costs of acquiring new software would make the model less accessible.

CHAPTER 4: THE CLEAR MODEL

Steve Higgins adapted the Spatially Explicit Individual Based Simulation model (SEIBS) to allow it to model populations instead of individuals, thereby making it suitable for landscape-scale studies. As SEIBS was no longer an appropriate name for it, and no alternative name was put forward by Higgins, the author of this report has chosen to call the model *Clear*, for the sake of simplicity, clarity and brevity.

The Clear model differs from the SELES model, which Higgins later developed for modelling the Cape Peninsula, in that it does not make use of the aggregated recruitment function. As the SELES model was set up specifically for the Cape Peninsula, it was not as suitable for general use as the Clear model. However, several improvements were still needed in order to make the Clear model suitable for wider use. This chapter describes the improvements made during the course of this study.

In order to understand the results produced by a model it is important to understand the nature of the input data as well as the processes that generate the results. The following sections, which describe the data requirements and internal workings of the model, provide this understanding. As no reference manual for the model exists, this chapter should be used as a first point of reference for future investigations.

4.1 DATA REQUIRED BY THE MODEL

Routines have been added to the model that allow spatial data layers to be uploaded. This allows heterogeneous environments that represent invasions in different areas to be modelled. It is also possible to enter a single value for any of the input layers, which will then be used as a homogeneous layer. The eight input data layers that can be specified are:

- Natural vegetation density
- Natural vegetation age
- Alien vegetation density
- Alien vegetation age
- Catchment boundary (optional)
- Dead areas (optional)
- Fire Zones (optional)
- Clearing preferences (optional)

The alien and natural vegetation density should be entered as the number of stems per hectare. The age of the plant should be entered in years. Alien and natural vegetation can occupy cells simultaneously. The presence of the other species does not influence the carrying capacity of the other vegetation type, but does influence the fecundity. It is possible to have alien vegetation age differing from the natural vegetation age, as the model takes into account that the older vegetation type may survive a fire, whereas the younger vegetation type may not.

A boundary can be specified, beyond which modelling will not occur. This may be a catchment boundary or any other suitable demarcation. If this layer is omitted, the entire rectangular extent will be modelled.

Areas such as water bodies, cultivated farmlands, towns and cities into which vegetation will not spread can be specified as dead areas. As seeds are not spread into these areas and these areas are not burnt, and germination will not occur within their boundaries. These areas are excluded from calculations of area.

In a large catchment or catchment of varying topography it is not likely that the entire area would burn in one fire season. Many factors influence the size of a fire. These include vegetation flammability, fire fighting actions, firebreaks, weather patterns and topography. In order to keep the model as simple as possible and to limit the amount of input data required, these factors are not modelled explicitly. A fire zone layer can be used to demarcate areas that are likely to burn as contiguous units. Topography, firebreaks, sub-catchment boundaries, old fire scars and expert knowledge should be used when identifying these units.

Clearing preferences can be indicated by creating a preference surface on which the values range from 1 to 10. Areas that are valuable due to high biodiversity, occurrence of endangered species or high water yield potential can be indicated as clearing priorities. The areas of highest priority must be given the highest preference value. ArcView contains all the necessary tools for creating such a surface from various data sources.

The scale and resolution of input data must be considered in the light of the chosen modelling resolution. A cell size of 10m may be suitable to represent individual plants when modelling *Pinus pinaster*. If the modelling is to be done at a landscape scale, which covers an area in the order of $100km^2$, modelling individual plants will not be computationally tractable as the computational demand increases rapidly with a decrease in cell size. Aggregating individuals into populations that are represented by a larger cell size ($\geq$100m) overcomes this problem.

In fynbos ecosystems fires cover large areas and recruitment largely occurs after fires. Consequently most stands of fynbos, including invaded stands, will tend to be even aged (Higgins, Richardson, Cowling & Trinder-Smith 1999). It is thus possible to model the population of a particular cell as being homogeneous in terms of age. The influence of spatial resolution on the spread rate is also an important consideration and is described in Chapter 5.

4.2 THE PROCESSES MODELLED

Modelling is carried out as yearly iterations. During each iteration, the following processes are executed in the order in which they are listed:

- Aging
- Disturbance (fire, point or block)
- Mortality
- Seed production and decay
- Seed dispersal
- Germination
- Prioritisation for management
- Management
- Annual statistics
- Output spatial data
- Display image

These processes are discussed below in more detail.

4.2.1 Ageing

The aging process is simple. During each iteration one year is added to the age of the natural and alien vegetation. When the vegetation is killed, the age is set back to zero and the aging process thus starts again.

4.2.2 Disturbance

The type of disturbances desired can be specified through the menu interface. Any combination of fire, point or block disturbance can be specified. The likelihood of mortality or germination in response to a disturbance can be specified through the model interface. A point disturbance disturbs a set number of individual cells at random, while a random block disturbance disturbs a block of cells of specified size.

The simulation of a fire regime is a more complex matter. In previous versions of the model, fires were initiated as a continuous front extending the width of the modelling area. It was a limitation of the model that fire could only be spread from the bottom to the top of the grid although the ability to model different fire spread directions could easily have been added. Fire was spread from one flammable cell to the flammable cells immediately to the top, left and right of it. This created an effect that was in some degree consistent with the effect of the South Easterly wind, which is the predominant wind during the fire season in the fynbos. These fires were thus only limited by availability of flammable vegetation. When modelling non-rectangular areas this method resulted in some areas never being burnt.

In reality, the size of a fire is also influenced by topography, prevailing weather conditions and fire fighting strategies. The incorporation of a digital elevation model would be a relatively simple matter as this data is readily available at suitable scales in most areas. Explicitly modelling factors such as weather conditions and fire fighting strategies would require a daily time step, together with historical meteorological time series data or area-specific fire statistics. This added level of complexity was not considered an immediate priority, as this study is focussed on testing the Clear models applicability, usefulness and user friendliness. It was recommended that a fire zones layer be used (Forsyth GG 2000 pers. comm.), as this would allow factors such as topography and the fire history of the area to be modelled implicitly.

The fire return interval in fynbos is typically between 8 and 25 years (Van Wilgen 1987) with extremes of 4 – 45 years. The relationship between probability of burning (p) and time (t) since the last fire is defined by the following hazard of burning function:

$$p=(1/b)^c * c * t^{(c-1)} \quad \textit{(Johnson \& Gutsell 1994).}$$

The method for determining b and c has been described by Le Maitre (1998). This hazard of burning function replaced both the ignition and spread functions originally used by Higgins in SEIBS and SELES. During each iteration, the probability of burning for each zone is compared against a randomly generated number. If the probability is greater than the randomly generated number the entire zone will be burnt. Figure 4.1 illustrates the relationship between the hazard of burning function and the resulting cumulative fire distribution. This figure shows that the model can closely simulate the fire distributions described in Le Maitre (1998). Figure 4.2

illustrates that the parameters chosen in this study are representative of fynbos fires in the Western Cape.

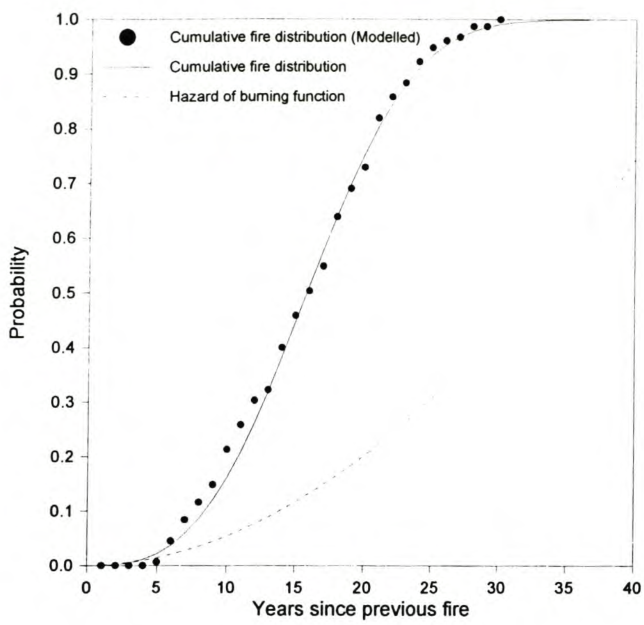


Figure 4.1:
Graph of fire hazard of burning function used in the model, the resulting cumulative fire distribution as well as the theoretical cumulative fire distribution curve.

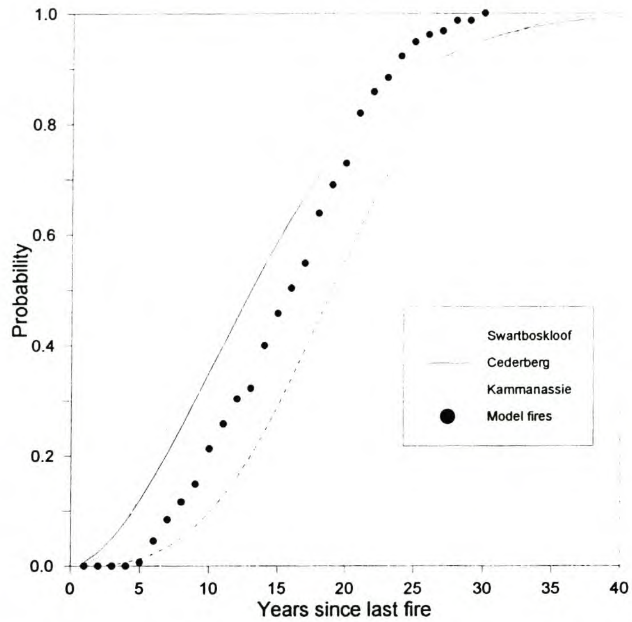


Figure 4.2:
Cumulative fire distribution curves for different areas together with the model predictions.

If a fixed fire return interval is specified, then fire zones will be burnt in regular succession according to the following equation:

$$ZoneID = year\ number - round(year\ number/fire\ frequency)$$

where ZoneID is an identity number assigned to each fire zone and round indicates that the number in brackets will be rounded off.

If no corresponding fire zone exists then no fire will occur. Fire zones with identity numbers higher than the fire return interval will never be burnt. For both the stochastic and fixed fire pattern, fires do not occur in the first four years of the model run. This allows for seeds to be distributed before the vegetation is destroyed.

The biological effects of fire differ according to the fire intensity and the stage of the annual reproductive cycle of the plant at which the fire occurs. Winter and spring fires are undesirable as the new fynbos seeds will be immature and will thus not be available to supplement seed stores (Van Wilgen, Everson & Trollope 1990). In the model, the season, climatic factors and fuel load were not taken into account in determining the biological effect of fire. Although this simplification is necessary to keep the model usable, deciding when to burn is an important management issue.

4.2.3 Mortality

The probability of natural die-off of vegetation, as well as mortality due to disturbance, is calculated as a function of age. This is illustrated in Figures 4.3 and 4.4 respectively. Mortality due to fires is the only disturbance considered in this study.

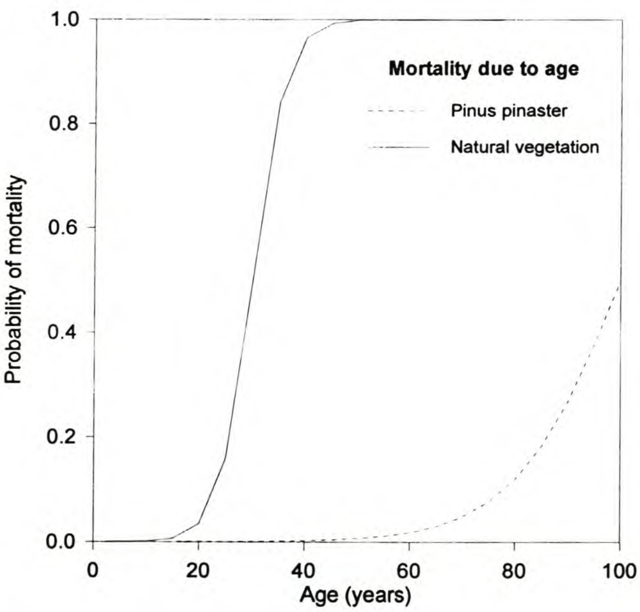


Figure 4.3:
Graph showing the relationship between natural die-off and age.

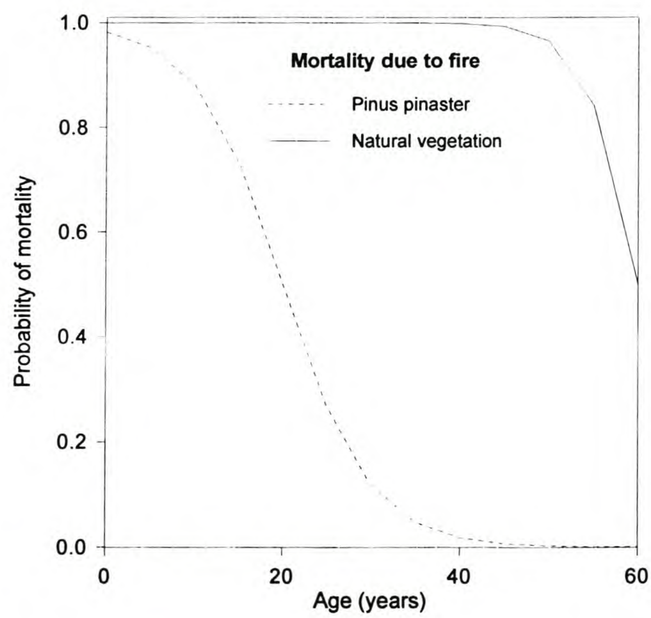


Figure 4.4:
Graph showing the relationship between mortality in the event of a fire and age.

4.2.4 Seed production and decay

Before new seeds are distributed, the proportion of seeds that decay every year is subtracted from the seed bank of each cell. The number of seeds available for dispersal for each cell is calculated by multiplying the number of stems by the fecundity (seed production per plant). The effect of biological control is incorporated at this point by multiplying the fecundity by (1–P) where P is the proportion by which seed production is reduced. In this study P=0 as no biological control is available for *Pinus pinaster*.

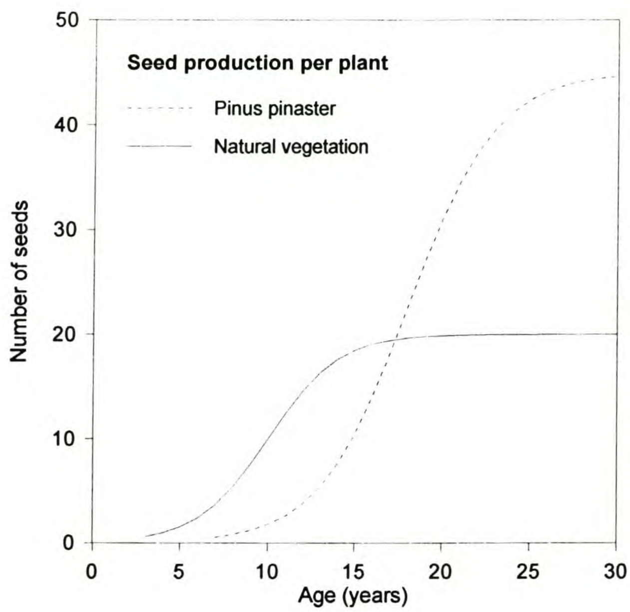


Figure 4.5: The potential seed production per plant as a function of age.

The potential seed production per plant (SP) is calculated as:

$$SP = f_m/(1+exp((f_{05}-age)/f_v))$$

The parameters f_m, f_{05} and f_v are coefficients which can be adjusted to change the shape of the curve which represents the relationship between seed production and age. The values used in this study are shown in Table 4.1 and the resulting relationship is illustrated in Figure 4.5.

In a crowded area the plants full seed production potential may not be realised. The actual fecundity is thus calculated by the following equation that combines potential seed production and plant density competition factors.

Setting Selfalpha to 0 implies that the presence of plants of the same type does not affect its fecundity. Setting Alpha to 0 implies that the presence of the other plant type does not affect the plants fecundity. Setting either Selfalpha or Alpha or both to a number greater than 0 will reduce the fecundity. The values used in this study are shown in Table 4.1.

$$fecundity = SP*(1-(stems_1*selfalpha+alpha*stems_2)/carry_1)$$

where $stems_1$ is the number of plants in question, $stems_2$ is the number of plants of the other type and $carry_1$ is the number of the plants in question that the cell can support.

Table 4.1: Fecundity parameter values used in this study.

Parameter	*Pinus pinaster*	Natural vegetation
f_m	45	10
f_{05}	12	5
f_v	4	3
Selfalpha	0	0
Alpha	1	0
Carrying capacity	400 plants/ha	1600 plants/ha

4.2.5 Seed Dispersal

Seeds are distributed as a function of distance from the centre cell. The proportion of seeds (P) falling into a one cell thick band with an outer border at a distance d_{out} away from the point of distribution is calculated as:

$$P=(1-exp(-d_{out}/s_1))-(1-exp(-(d_{out}-cellsize)/s_1)).$$

Here s_1 represents the distance within which the majority of the seeds would fall. The proportion of seeds is then divided by the number of cells in the band resulting in an even spread in all directions. In the case of seeds where wind would effect the direction of the dispersion it would be desirable to be able to specify this in the model. This component could be added to the model, however it was not done here for the sake of simplicity. As the majority of seeds tend to fall within a few metres of their parent plants they will not be dispersed far enough to reach a neighbouring cell if the model is run at a coarse resolution.

With the help of dispersal agents such as birds, animals, rivers and strong winds long distance dispersal events can take place. These events have been noted to be of critical importance in determining the rate of invasions (Higgins and Richardson 1999) and thus the model allows for a proportion of the seeds to be dispersed at greater range of distance. The distance (D) these seeds will travel is calculated as:

$$D = - s_2 * ln(1*random)$$

where random represents a randomly generated number between 0 and 1 and s_2 is the maximum distance seed can travel with the help of dispersal agents.

The values for s_2 used in the study are shown in Table 4.2. These seeds are dispersed in a random direction which is appropriate for plants with dispersion agents such as birds or animals. However in the case of wind dispersed seeds it would more accurate to specify the direction in which seeds were distributed. Once again this component could be added to the model, however it was not done here for the sake of simplicity.

Table 4.2: Dispersal parameters used in this study.

Parameter	*Pinus pinaster*	Natural vegetation
P	0.98	0.98
s_1	10 m	10 m
s_2	500 m	100 m

The long distance dispersal distances achieved for *Pinus pinaster* using the parameters in Table 4.2 are shown in Figure 4.6. Figure 4.7 was generated by predicting the long distance dispersal distance for 49 evenly distributed values between 0 and 1. This serves to illustrate the effect of the curve in Figure 4.6. We can see from the bar chart that about 20% fall within 100m, about 30 % fall within 200m, about 60% fall within 500m, while about 10% travel further than 1000m.

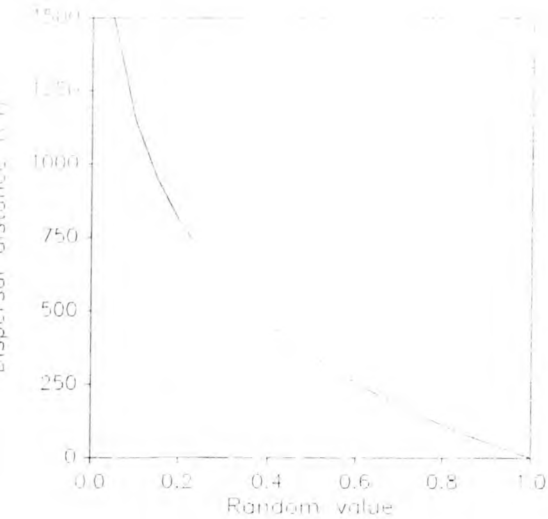


Figure 4.6:
Graph showing relationship between dispersal distances and random number generated.

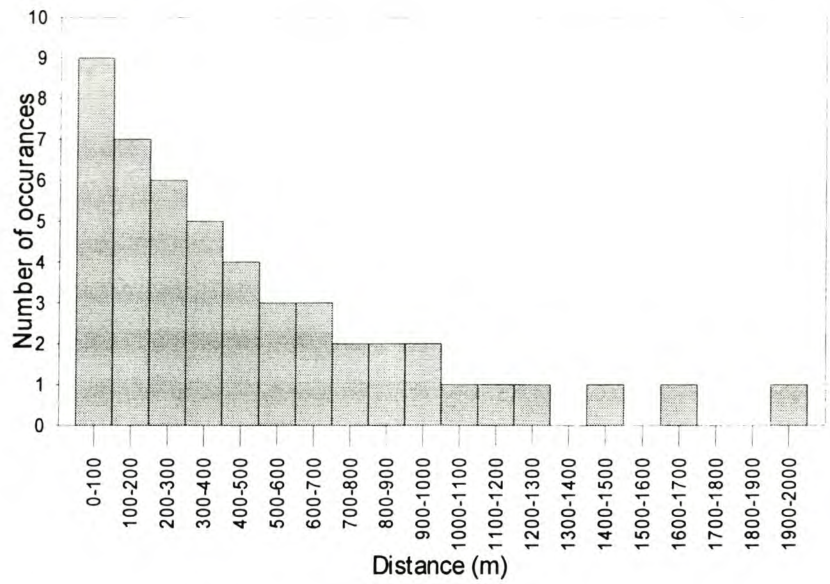


Figure 4.7:
Graph showing occurrence frequencies for distance categories.

When seeds are assigned to cells they are added to the existing seed bank of the cell. These seeds are now available for the next process – germination.

4.2.6 Germination

Through the disturbance pattern interface the user can specify whether fire, point and or block disturbance will result in seed germination. Fires and disturbances therefore create recruitment opportunities by providing the seedlings with the necessary space and sunlight to grow. In the Clear model successful recruitment occurs only if the sight is unoccupied. Fynbos and most species of invasive pines in fynbos are serotinous, which means that germination occurs mainly after fires (Richardson & Brown 1986). In order to simplify the model, it is assumed that germination occurs only after fires. In the absence of factors which normally limit fecundity in their native habitat, alien populations often show an excessive increase following fire (Richardson & Brown 1986). Alien seedlings are assumed to be more competitive than the natural vegetation and thus alien seeds are given the first chance at germinating in the available sites.

4.2.7 Prioritisation for clearing

The clearing operation takes place at clearing sites or windows, which consist of a number of cells. The increased size of the management site not only dramatically increases the speed at which the model runs, but should also represent the actual size of management sites more realistically than the cell size. Each year management sites are cleared according to their priority score until the money runs out. The priority score for each management site is calculated using the following equation:

Overall score for window=1000(adensity*weight_dense+repro*weight_repro +ndensity*weight_native+burnt*weight_burnt+pref *weight_pref)*

where adensity, repro, ndensity, burnt and pref are as described in Table 4.3 and weight_dense, weight_repro, weight_native, weight_burnt and weight_pref are the weightings ascribed to each factor.

Table 4.3: Equations used to calculate scores for factors that contribute to the overall score of a window of cells.

Priority setting	Calculation of parameter
Dense areas of alien vegetation are prioritised	adensity = (number of alien plants) / carrying capacity
Sparse areas of alien vegetation are prioritised	adensity = 1 - (number of alien plants) /carrying capacity
Adult plants are prioritised	repro = (number of adult plants) / carrying capacity
Juvenile plants are prioritised	repro = (number of juvenile plants) / carrying capacity
Dense areas of natural vegetation are prioritised	ndensity = (number of natural plants) / carrying capacity
Sparse areas of natural vegetation are prioritised	ndensity = 1 - (number of natural plants) /carrying capacity
Burnt areas are prioritised	burnt = number of burnt cells /number of cells in window
Non burnt areas are prioritised	burnt = 1- number of burnt cells /number of cells in window
Preference areas are prioritised	pref = preference score for window/(number of cells in window *10)
Preference areas are avoided	pref = 1- preference score for window/(number of cells in window *10)

4.2.8 Management

An integrated approach involving the combined use of a range of methods is usually necessary to control invasive plants effectively. Approaches available for integrated control depend on the species under consideration, features of the invaded systems and the availability of resources (Van Wilgen, Richardson & Higgins 2000). The management component of the Clear model allows for the evaluation of various control strategies. The model can simulate the following management options:

- Herbicide application;
- Biological control;
- Clearing; and
- Fire management.

These options can be used in combination and the order in which they are carried out can be specified. This study only focussed on the use of mechanical clearing as this is recognised as the most effective strategy for clearing *Pinus pinaster* (Stirton 1980). The model originally allowed for cost of clearing per ha to be broken down into three density classes, which were further classified as either initial clearing or follow-up areas. The values used in the ACMS model (Muller 2000) are presented in Table 4.4.

Table 4.4: Costs per ha of clearing *Pinus pinaster* associated with different alien vegetation classes, as used in the ACMS model.

Density	Initial	Follow up
High (>75% of carrying capacity)	R3844	R818
Medium (between 25 and 75% of carrying capacity)	R1112	R512
Low (<25% of carrying capacity)	R585	R249

The costs in Table 4.4 are based on earlier clearing results and in future will need to be adjusted to reflect factors such as improvements in clearing efficiency and inflation, in order to obtain more accurate cost estimates. However, the cost estimates in Table 4.4 are adequate for the purpose of demonstrating the usefulness of the model.

Calculations based on costs specified for such broad density categories proved problematic and thus it was decided to experiment with a costing scheme based on number of trees cleared. The amounts in Table 4.5 were based loosely on the costs in Table 4.4 and a maximum carrying capacity of 400 trees per ha. It is acknowledged that the carrying capacity is much higher than this in juvenile stands, but a fixed maximum carrying capacity is one of the underlying assumptions of the model. Richardson & Brown (1986) reported stands of densities up to 1000 stems/ha for *pinus* species. This density is expected to decrease to about 400 stems/ha as the trees grow and compete for sunlight and space (Le Maitre DC 2000 pers. comm.). Further model tests should be conducted with higher maximum carrying capacity to examine its sensitivity to this parameter. Although it would require an added level of complexity and substantial alterations to the model code, a function to relate carrying capacities to age could be introduced.

The reduced cost of clearing trees in denser stands is based on the supposition that teams work more effectively in dense stands where progress is more obvious, and that working in lightly infested areas increased the logistical complexity of operations and required a higher management-to-worker input ratio (Versfeld, Le Maitre & Chapman 1998).

Table 4.5: Costs of clearing individual *Pinus pinaster* trees.

Density	**Adult**	**Juvenile (< 5 years)**
Medium and high (between 25 and 100% of carrying capacity)	R10	R5
Low (between 5 and 25% of carrying capacity)	R11	R6
Scattered (<5% of carrying capacity)	R12	R7

This different pricing structure is experimental and has not yet been evaluated. The code can easily be changed back to the original cost structure or any other costing structure for that matter. A further experimental addition to the costing component is the introduction of the ability to specify the cut-off age for plants to be classified as juvenile for costing purposes and the ability to specify a fixed cost per hectare. Another interesting development which was considered, but not implemented, would be to include a cost surface which could include the added cost of reaching sites which are less accessible due to distance from towns or roads, or situated at higher altitudes or on steep slopes.

Although the model can provide a relative costing of various clearing strategies, the current simplified costing routines do not provide an accurate budgeting tool. Further

investigation is needed in order to establish how best to incorporate the added levels of complexity needed to provide a more flexible and accurate budgeting facility.
An initial lag period before which no clearing occurs, together with a constant annual clearing budget, can be specified through the user interface. Alternatively, a budget file containing a varying yearly budget can be uploaded. In each iteration sites are cleared according to their priority values until the budget for the year is exhausted.

4.3 THE MODEL INTERFACE

The model interface consists of dropdown menus, input screens, control buttons as well as a graphic and text display. The graphic display is updated every time step and provides an animated overview of the alien invasion. The display shown in Figure 4.8 is the stems display in which the different vegetation types are represented by different colours. Green represents areas of natural vegetation, yellow represents areas of mixed natural and alien vegetation, while red indicates areas where only alien vegetation exits. Black areas are cells where no vegetation exists. The white areas are out of bounds areas into which vegetation can not spread.

The *Display* radio button can be used to switch to a display in which the seeds are displayed using the same colour scheme or to switch to the *Disturbance* display which indicates burnt or disturbed areas in red against a black background. The *Text* display provides a summary of key variables.

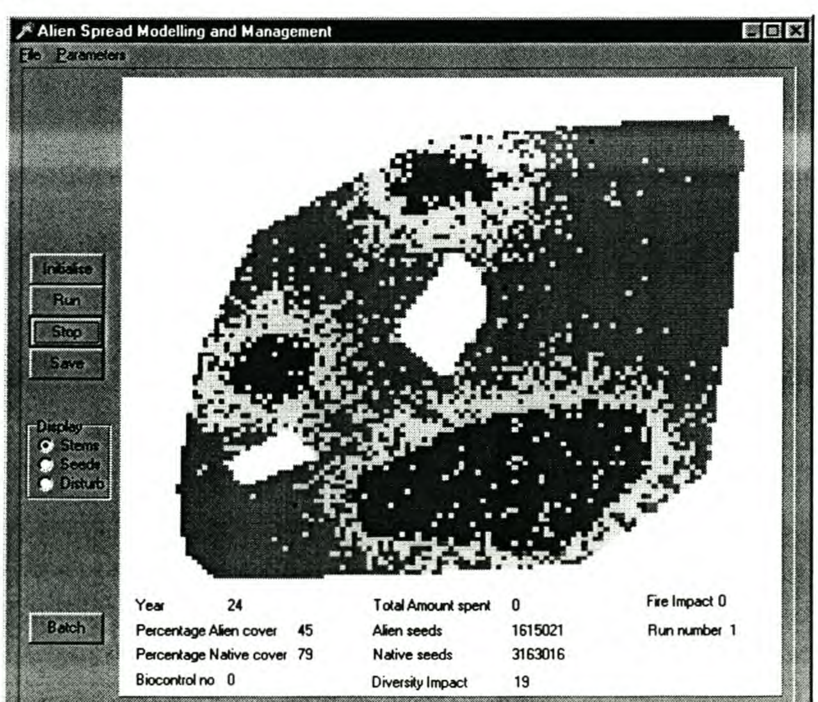


Figure 4.8: The model interface.

The File Menu

The *File* dropdown menu (Figure 4.9) allows for the uploading of the advanced demographic settings parameter file. Adjustments to the parameters can also be saved for future use. GIS layers, which have been generated using the Alien Spread Modelling extension in ArcView, can be uploaded. By selecting the correct asm_info.txt file, which will have been automatically created along with the spatial data layers, the layers are uploaded simultaneously. The menu items on the *File* menu are listed in the order in which they are most likely to be used.

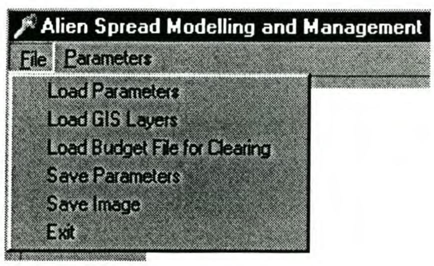


Figure 4.9: The File dropdown menu.

The Parameters Menu

The options on the *Parameters* menu (Figure 4.10) can be used in any order. The *Management Options* form is the form most likely to be edited by all users.

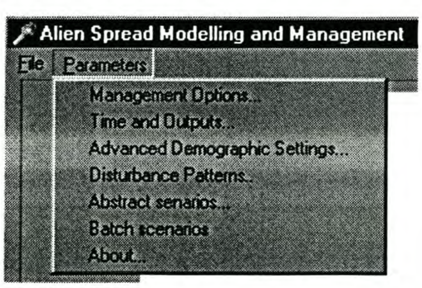


Figure 4.10: The Parameters menu.

The Management Options and Site Priority Forms

The M*anagement Options* form (Figure 4.11) consists of seven components. The *Clearing site* component allows for the side length of a square management site to be defined in terms of cells. It also provides a link to the *Site Priority* form (Figure 4.12) in which the clearing priorities and weightings can be entered.

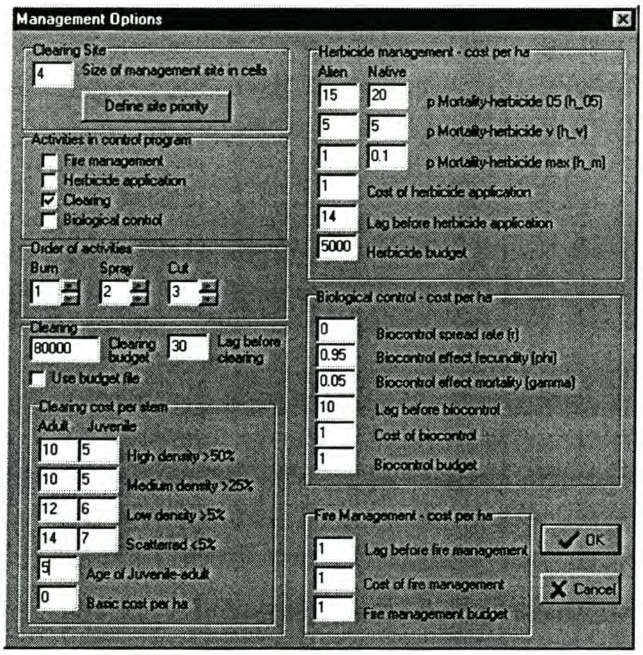


Figure 4.11: The Management Options form.

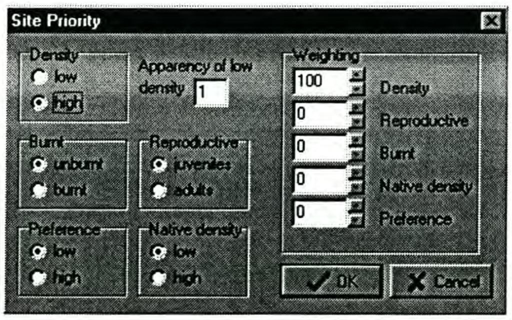


Figure 4.12: The Site Priority form.

The *Activities in control programme* component together with the *Order of activities* component allows for the selecting, combining and ordering of management activities. The *Clearing* component facilitates the inputting of budget related information as well as the specification of a lag period after which management activities commence. The monetary values are relative to each other and thus not tied to any currency unit. By selecting the *Use budget file* option and uploading a budget file via the *File* menu, the user is able to simulate budgets that vary on a yearly basis.

The Time and Outputs Form

This form allows the user to specify the frequency and type of spatial outputs they require as outputs from the model. Users are free to change the settings on the *Time and Outputs* form (Figure 4.13) as it will not influence other processes in the model.

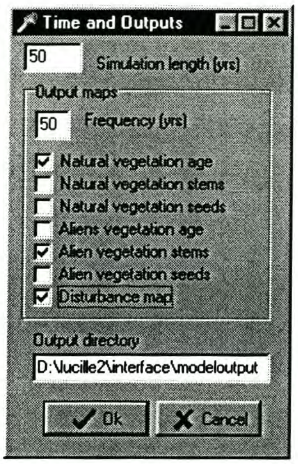


Figure 4.13: The Time and Outputs form.

The Advanced Demographic Settings Form

The *Advanced Demographic Settings* form (Figure 4.14), however requires expert knowledge and users are warned against editing values without expert advice.

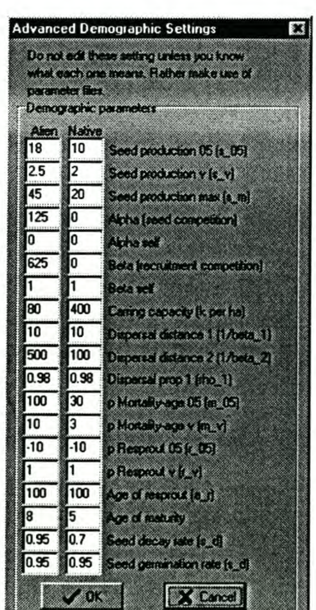


Figure 4.14: The Advanced Demographic Settings form.

The Disturbance Patterns Form

The *Disturbance Patterns* form (Figure 4.15) also requires expert knowledge. It allows the parameters for fire and other disturbance patterns to be altered.

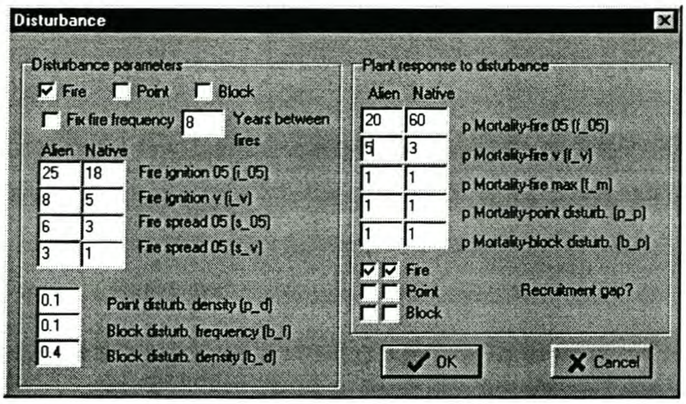


Figure 4.15: The Disturbance Patterns form.

The Abstract Setting Form

In the absence of spatial data, model runs can be conducted using an abstract pattern of vegetation cover. The settings for this can be altered via the *Abstract Scenarios* form (Figure 4.16).

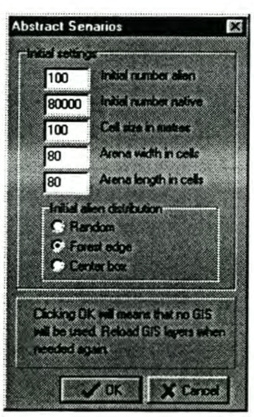


Figure 4.16: The Abstract Scenarios form.

The Batch Scenario Form

Due to the stochastic nature of the model routines, it is desirable to run many iterations in a batch mode. The *Batch Scenarios* form (Figure 4.17) allows for the specification of a file that contains the list of scenarios to be run. The two output filenames capture the pertinent variables for each run. The first file writes out the total amount spent clearing as well as the number of years before the alien vegetation is eradicated. The second file captures the number of alien and natural vegetation stems as well as the percentage of area burnt each year.

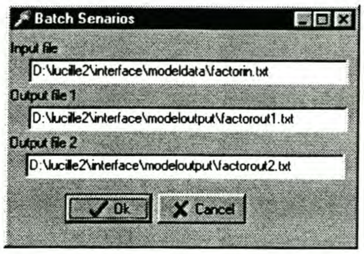


Figure 4.17: The Batch Scenarios form.

The About Form

The *About* form (Figure 4.18) explains the origin of the programme and gives credit to the original developer of the programme. It explains that the additions made by the author of this report were primarily to allow for the efficient input and output of GIS data. The user is also notified of the new fire routine, which significantly altered the behaviour of the model. Other changes incorporated by the author of this report were aimed at making the interface easier to use and were therefore mainly cosmetic. These changes include: the incorporation of a budget file; the ability to fix the fire return interval; the re-organisation of form and menu items; and allowing for density dependent costing for clearing.

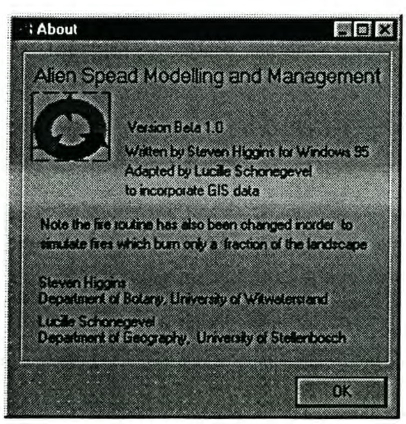


Figure 4.18: The About form.

4.4 THE USE OF THE CLEAR MODEL AS A DECISION SUPPORT TOOL

Current management decisions are based on a combination of scientific advice and trial, error and continual improvement. Allowing managers to do hundreds of "trial and error" runs in order to explore the consequences of certain courses of action should allow for better decision making (Van Wilgen, Richardson & Higgins 2000). The Clear model therefore provides a valuable decision support tool as it allows clearing strategies to be tested. In Table 5.3 we can see the effect of using different clearing strategies which prioritise different vegetation classes. Strategies which prioritised the clearing of juvenile and sparse vegetation were more efficient than those which prioritised the clearing of dense or adult vegetation. This section describes two more clearing strategy tests to further illustrate how such tests might influence decision making. In both tests the clearing of sparse vegetation was prioritised.

The first test examined the effectiveness of five different annual clearing budgets. Figure 4.19 shows that the time taken to clear an area reduces rapidly with an increase in spending. The total cost of the clearing operation is also reduced (Figure 4.20) if the annual budget is increased. If the annual budget drops below a certain threshold, the clearing programme will merely slow down the invasion. In the test case examined here it appears that an annual budget of less than R10 000 was insufficient to clear an invasion of 2600 pine trees and their progeny. This cost estimate need not closely resemble the input costs in Section 4.2.8 as the model result is based on a complete series of interactions between spatial and temporal factors over more than one reproductive cycle.

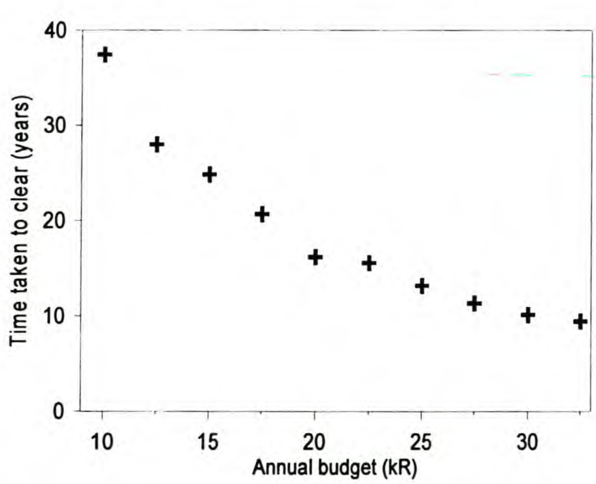


Figure 4.19: The influence of annual spending on the time taken to clear alien vegetation.

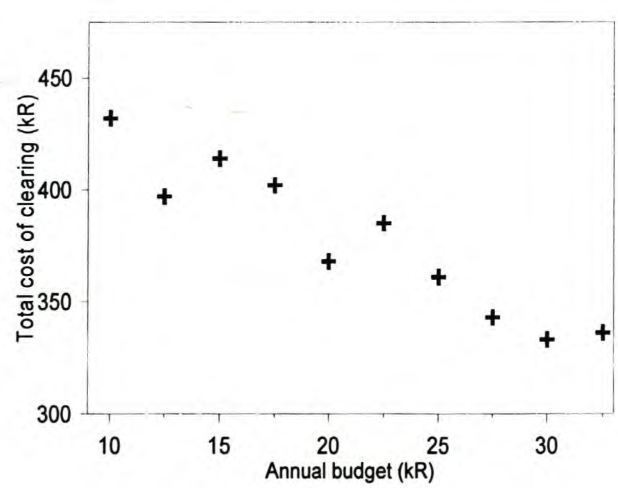


Figure 4.20: The influence of the annual budget on the total cost of clearing.

The second test examined the effect of delaying the clearing operation. Although it is not clear from the results of this test (Figure 4.21) whether the relationship between the total cost of clearing and delay is linear or exponential, it is clear that the cost of delay is severe. The tests were carried out with delay periods of 20, 25, 30 and 35 years in order to simulate the clearing of an area with a well-established invasion. Delaying the clearing operation from 20 years to 25 years resulted in a 15% increase in cost, while delaying for a further 10 years resulted in a further 45% increase in cost. The results presented here each represent the mean value of 50 runs or simulations and are general trends, not hard and fast rules. Due to the stochastic nature of certain model processes, the standard deviations from the means were high in all cases. These effects may be more or less pronounced under different conditions. In his study of the Cape Peninsula, Higgins (1998) presents a more detailed analysis of the effects of various prioritisation schemes, of delaying the start of clearing and of increased annual spending.

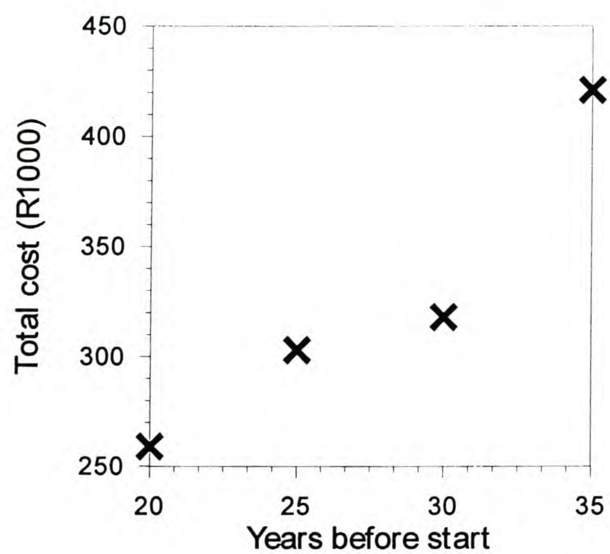


Figure 4.21: The financial implications of delaying the start of a clearing programme.

4.5 VERIFICATION, VALIDATION AND TRANSPARENCY

If actions are going to be taken based on model predictions, it is important to verify and validate the model. Verification is the test of the internal logic of a model, whereas validation is the comparison of model output to independently measured data (Morain 1999). It is also important that the model is transparent. Transparency must ensure that the user of a model is aware of:

- The specific problems the model is capable of addressing;
- The assumptions made concerning ecosystem processes;
- The temporal and spatial scales at which the simulation occurs; and
- The extent to which the model has been validated.

The specific problems the model can address and the assumptions made were described in Chapter Four. The model operates on a yearly time step and therefore is suited to long-term simulations. The spatial scale at which the model is applied may vary greatly. In order to evaluate the ease at which the model can be set up for new areas, it is important to understand the influence of spatial scale and characteristics such as fragmentation and heterogeneity. These aspects are investigated in Chapter Five.

The verification and validation of the SEIBS and Clear models has been documented elsewhere in the literature (Higgins 1998 and Higgins, Richardson & Cowling 1999b). As the modifications needed to incorporate spatial data and the alterations to the clearing budget routine did not change the internal logic or assumptions of the programme, it was not believed to be necessary to conduct another exhaustive validation. The only process in the model that has been significantly altered since the last validation study was the fire regime. The study of the model's sensitivity to the size of fire zones (Section 5.3) and fire occurrence patterns (Section 5.4) will serve as an indication of the robustness of the new fire regime.

CHAPTER 5: SENSITIVITY TO SPATIAL CHARACTERISTICS AND FIRE OCCURRENCE

In order to model areas of different scales, starting configurations and fire regimes it is important to evaluate the model's sensitivity to these aspects. The fundamental process underlying all model tests is plant spread. If the spread is accurately modelled then costs of clearing operations can be confidently derived. The number of plants in an invasion, as well as the invaded area, increases as a function of time. Comparisons of invaded area and number of plants are presented together in this section as they both provide insight into the invasion process.

There have been remarkably few empirical studies that have quantified the rate of plant invasions. Although there have been a few South African studies which analyse changes over time, only four studies could be found which provided sufficient data for parameterising a spread model over time (Versfeld, Le Maitre & Chapman 1998). Two of these studies focused on *Acacia species*, one on *Prosopsis* and one on *Pinus radiata*. More recently, Higgins reconstructed the invasion histories for four sites invaded by *Pinus pinaster* and two sites invaded by *Acacia cyclops* (Higgins 1998). The empirical studies indicate that the expansion rate of invading species goes though three phases:

- A lag or delay during which the plants reach maturity or build up to a level at which new colonisation begins;
- A rapid expansion stage, frequently exponential; and
- A gradual slowing down of the expansion rate as the potentially invadable area decreases.

The following spread function provides a simple and suitable model for describing the expansion of the invaded area as it goes through the three phases:

$$N_t=N_{t-1} + r(1-N_{t-1}/K)N_{t-1} \quad \textit{(Versfeld, Le Maitre \& Chapman 1998)}$$

where:
N is the number of individuals or habitat units occupied
t is the current time step and t-1 the previous time step
K is the carrying capacity or number of habitat units that can be occupied
r is the intrinsic (maximum) rate of spread.

Due to the impracticality of counting thousands of trees in the field or on aerial photographs, no calibration data is available against which to compare the numbers of trees. Therefore expansion rates of the invaded area have been compared instead. Richardson & Brown (1986) give the expansion rate of *Pinus radiata* as about 0.2 which is probably unreasonably high (Versfeld, Le Maitre & Chapman 1998). This high rate of spread can probably be attributed to a dense stand of trees neighbouring the study area that contributed significantly to the rate of recruitment. The rates of invasion estimated by Higgins (1998) from historical photographs ranged between 0.027 and 0.062. These values represent the intrinsic or maximum spread rate as used in the spread function. Four expansion curves derived from the spread function are plotted in Figure 5.1. These curves illustrate the three phases of expansion and provide a comparison for the modelled expansion curves which are presented in the following three sections.

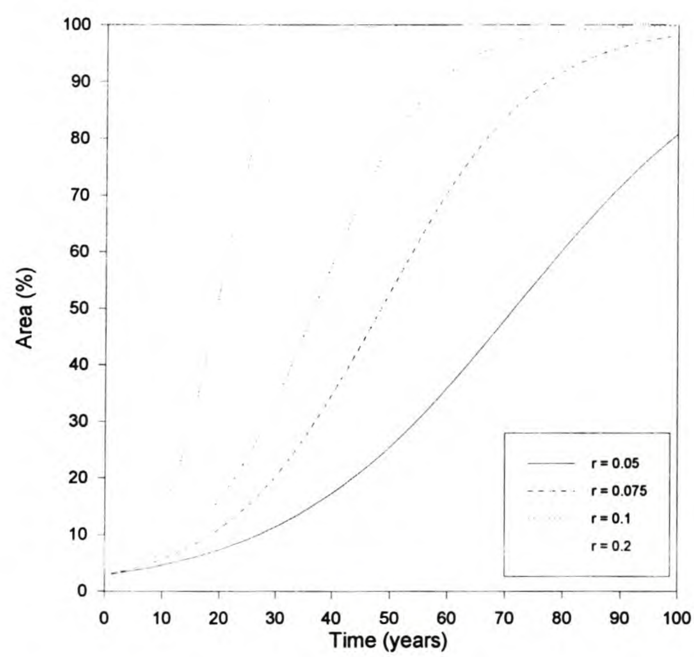


Figure 5.1: Comparison of spread functions for various intrinsic spread rates (r).

5.1 SPATIAL RESOLUTION

Landscape patterns and ecosystem processes are often interrelated in a complex manner that is dependent on the scale at which the ecosystem is considered. As the Clear model is a cell-based model, the influence of heterogeneity changes with cell size. A variety of cell sizes need be used in order to model areas varying in size from 1km to100km. In order to strike a balance between fine scale resolution and modelling speed, it is recommended that the grids used for modelling should contain between 100x100 and 200x200 cells. Table 5.1 serves as a guideline as to the range of cell sizes suitable for modelling different sized areas.

Table 5.1: Recommended cell sizes for different modelling extents

Modelling extent (m)	Recommended cell size (m)
1000 x 1000	5 - 10
10 000 x 10 000	50 - 100
20 000 x 20 000	100 - 200
50 000 x 50 000	250 - 500

In this study three scenarios with cell sizes of 50mx50m, 100mx100m and 200mx200m were tested. Figure 5.2 shows the invasion after 30 years for an individual run for each of the three resolutions. Again it must be noted that due to the stochastic nature of many of the model processes, the same set of parameters will produce different results each time the model is run. Therefore, the illustrations in Figure 5.2 each represent only one of a myriad of possibilities.

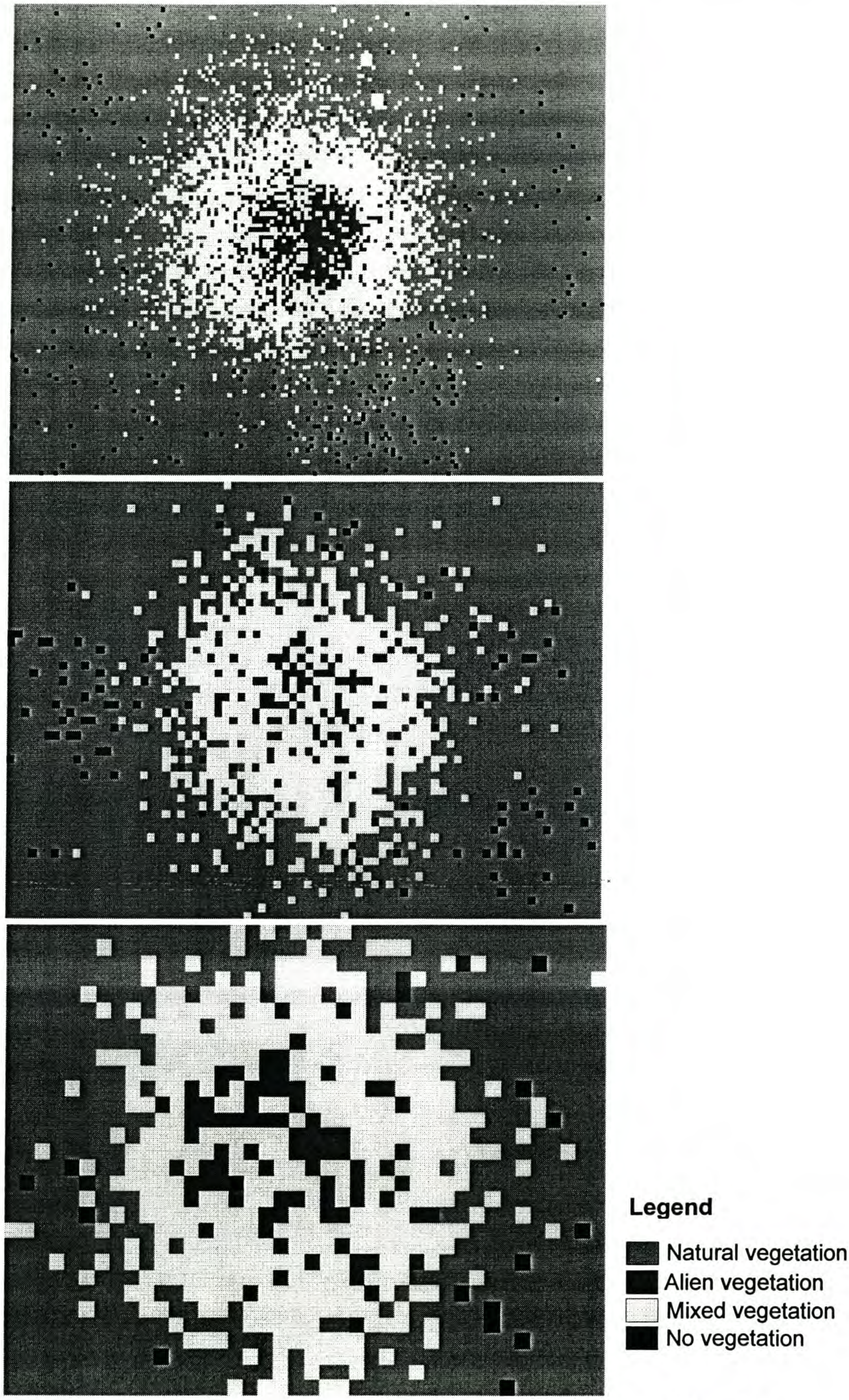


Figure 5.2: Illustrations of model layers with cell sizes of 50mx50m, 100mx100m and 200mx200m.

The model was run 100 times for a period of one hundred years for each scenario. The results presented in Figures 5.3 and 5.4 represent the mean values of the 100 runs. The comparison of the area curves presents a problem as the areas have been calculated at different scales. All cells including alien stems are included in the calculation. Whereas 250m^2 is added to the area each time a new cell is colonised in the 50mx50m scenario, 10000m^2 and 40000m^2 are added in the 100mx100m and 200mx200m scenarios respectively. Thus the differences seen in Figure 5.3 are artefacts of scale and indeed no conclusions can be drawn from these calculations of area.

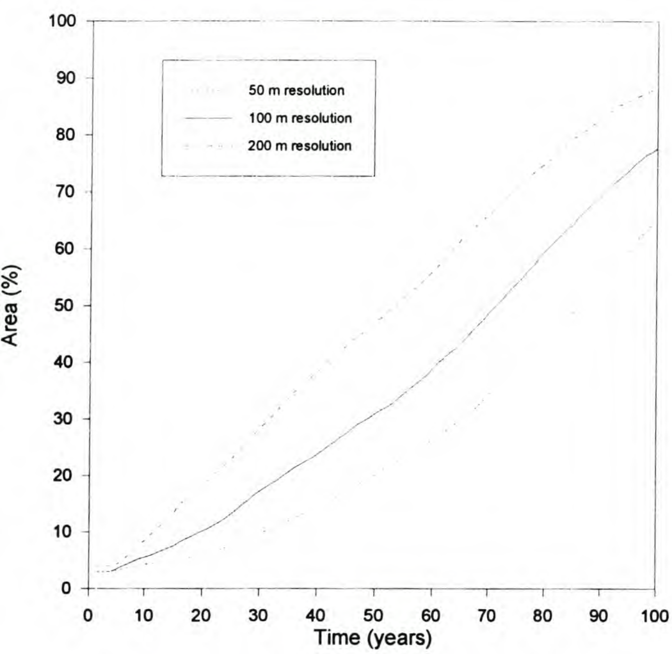


Figure 5.3:
Graph showing effect of spatial resolution on the rate at which the invaded area increases.

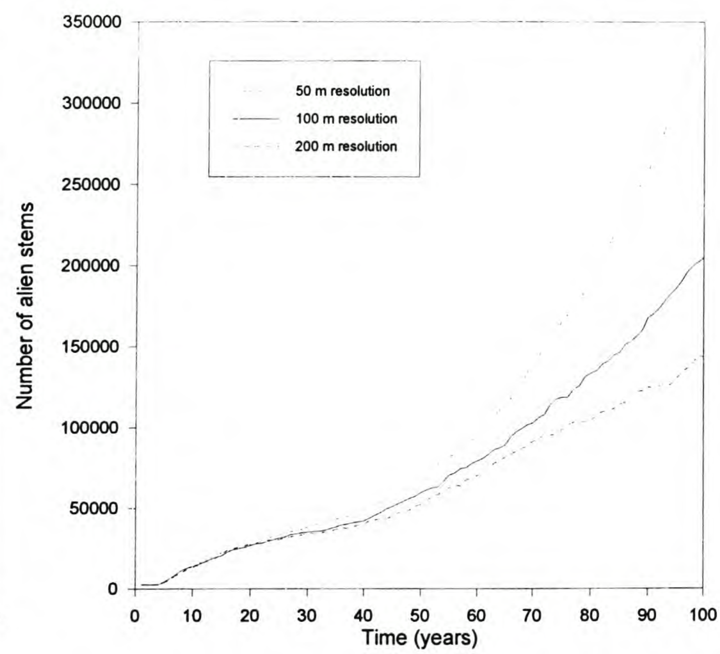


Figure 5.4:
Graph showing effect of spatial resolution on the rate at which pine trees increase in number.

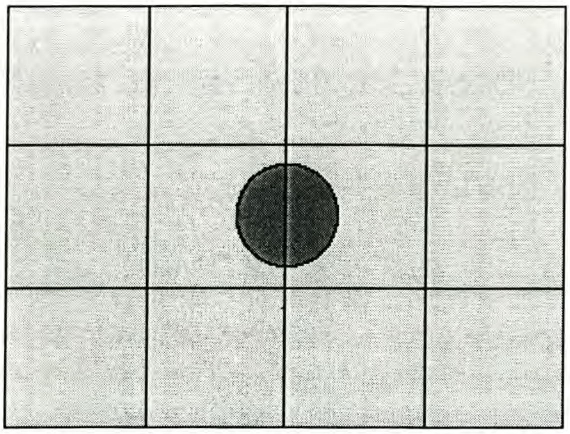
The results presented in Figure 5.4 provide for an interesting analysis. From the graph we can see that after an initial lag period of about 20 years, a marked difference in the rate of increase can be seen between the three scenarios, with the finer scale scenario increasing more rapidly. The area modelled was 4800ha. A carrying capacity of 400 stems/ha was specified for *Pinus pinaster* and thus the total carrying capacity for the modelled area is 1 920 000. As this number of stems is not approached, we do not see the flattening off of the curve that is characteristic of an invasion approaching saturation.

It was initially thought that the seed dispersal function would result in discrepancies in spread rates at different scales. The seed dispersal distance is specified as two distances which represent short-range and long-range dispersal. If this short-range dispersal distance is less than half the cell size, then none of these seeds will leave the cell. This is the case for all three scenarios modelled here and thus the difference noted in the spread rate cannot be attributed to the short-range dispersal parameter.

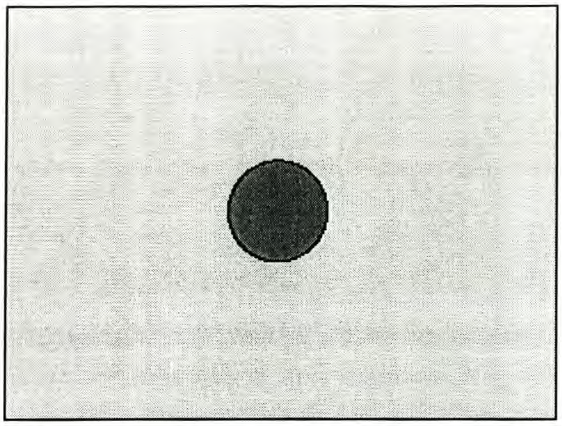
Most of the seeds that are distributed according to the long-range dispersal distance curves illustrated in Figure 4.5 and 4.6 leave the parent cell. About 10 to 20% fewer seeds will reach new cells when modelling at the coarser resolutions. This becomes insignificant in the light of the fact that each new cell reach at a coarser scale is 400 to 1600% larger in area. The larger cells have proportionally higher carrying capacities and thus it would be expected that the numbers of alien plants would increase more rapidly at larger resolutions. However, Figure 5.4 shows that this is not the case. As this result was counter intuitive, careful thought had to be given to the influences on scale on each of the processes modelled. The germination routine was considered after investigating the distribution routines provided no further insight.

Alien seeds only germinate if a fire has occurred in the fire zone and the old alien vegetation has died. The parameters used in this study specified that 50% of trees of age 20 would survive a fire, with mortality at other ages fitting the curve depicted in Figure 4.3. Twenty years is close to the average fire frequency and thus a large proportion of the pine populations survive the fires. The dense seed banks that have built up in these cells therefore are not able to germinate and add to the density of the cell. At a coarse scale this problem is more severe as one old, established pine tree can dominate a larger area. This poses an interesting problem for the modeller, as single aged populations are one of the Clear models fundamental assumptions. It is essential to have some older trees survive the fire, as this is what occurs in reality. However, having relatively few trees prevent germination in a large area is not realistic.

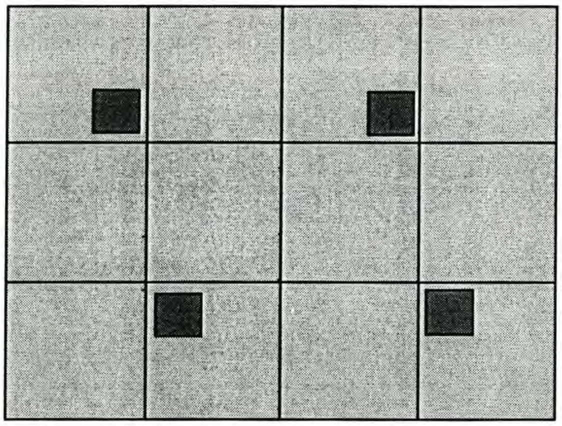
It can thus be concluded that the invasion is strongly influenced by the scale at which the modelling occurs. Higgins parameterised his model for *Pinus pinaster* using a 100m cell size. In order to avoid reparameterising the model, a 100m cell size was used in all other parts of this study.



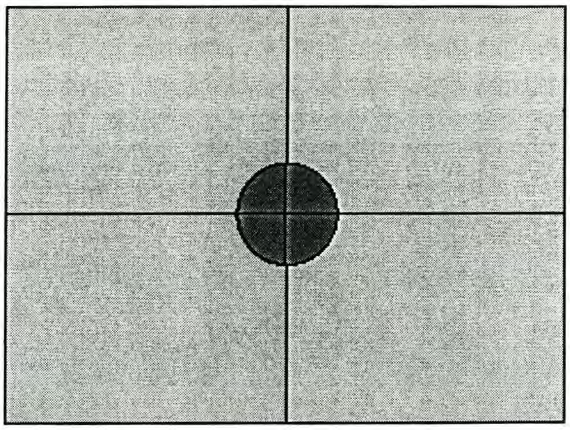
A One starting circle of alien plants and twelve fire zones.



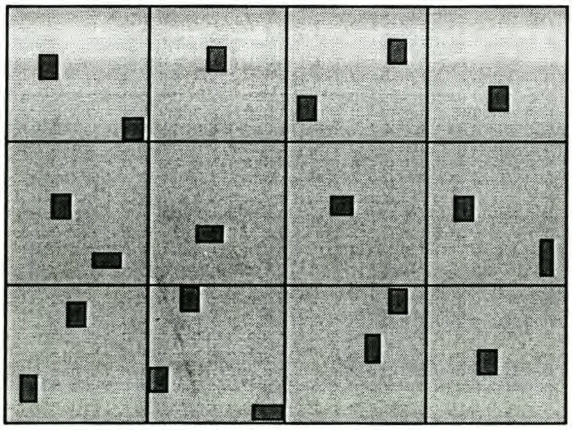
D One starting circle of alien plants and one fire zone.



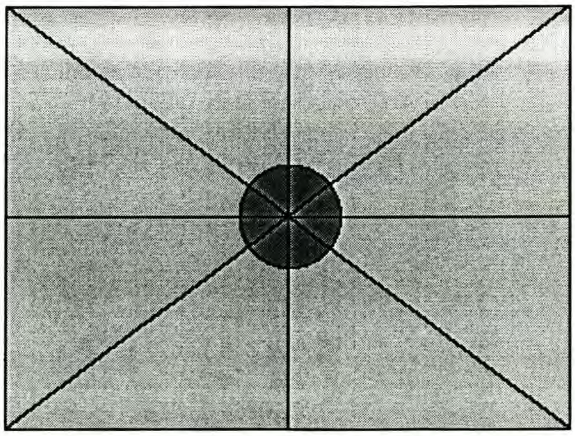
B Four starting blocks of alien plants and twelve fire zones.



E One starting circle of alien plants and four fire zones.



C Sixteen starting blocks of alien plants and twelve fire zones.



F One starting circle of alien plants and eight fire zones.

Figure 5.5: The spatial data layers used as input in the various model scenarios.

5.2 SPATIAL FRAGMENTATION OF ALIEN VEGETATION

In this section three scenarios differing in initial spatial fragmentation are compared in order to illustrate the effect of the initial spatial fragmentation on the spread rate of the invasion. Figures 5.5 A-C show the starting conditions for the three scenarios compared. The first scenario started with a single circular patch of aliens. The second and third scenarios consisted of four and sixteen scattered blocks of alien vegetation respectively. The density of each of the patches was 16 stems per hectare while the total area invaded was 166 ha in each scenario. The model was run 100 times for a period of one hundred years for each scenario. The results presented in Figures 5.6 and 5.7 represent the mean values of the 100 runs.

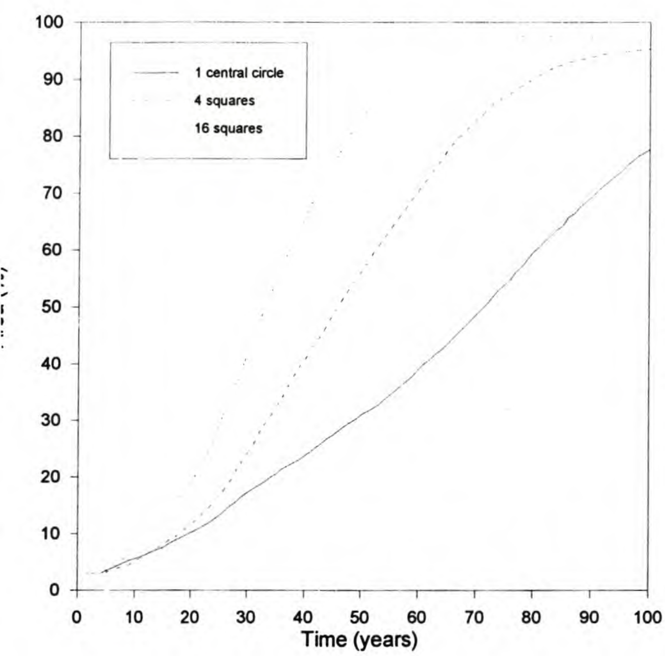


Figure 5.6:
Graph showing effect of initial spatial fragmentation on the rate at which the invaded area increases.

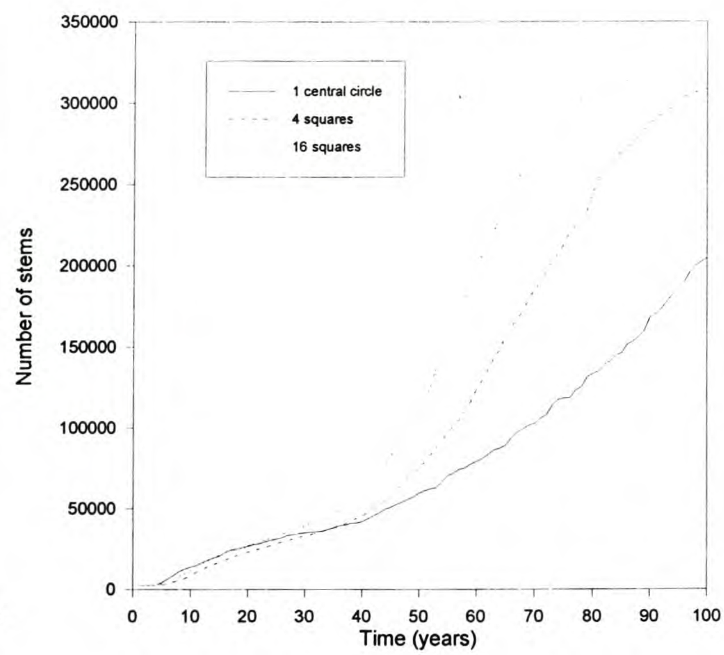


Figure 5.7:
Graph showing effect of initial spatial fragmentation on the rate at which pine trees increase in number.

Figures 5.6 and 5.7 illustrate that a more scattered invasion poses a greater management problem. The marked difference in spread rate can be attributed to the fact that many more uninvaded cells lie next to invaded cells due to the larger invasion circumference. As many more seeds fall into uninvaded cells, the invasion spreads more rapidly. This finding is supported by a modelling study by Auld and Coote (1980) where they found that a scattered initial population had a greater rate of spread and population growth rate than a central population. Comparing Figure 5.1 and Figure 5.6 shows that the range of spread rates achieved here are similar to the range of spread rates quoted in the literature. In fact, the single circle spread curve fits the r = 0.05 curve, the four squares curve can be approximated by the r = 0.075 curve while the sixteen squares curve is similar to the r = 0.1 curve (refer to Figure 5.1). Many simpler models such as the ACMS model use one spread rate for all starting configurations. As can be seen here this is gross generalisation. However, if the ACMS model is being used for coarse scale budgeting and prioritising, as was intended, then this simplification is acceptable. Further empirical studies need to be conducted in order to provide better estimates of spread rates under different initial conditions.

The graph of plant numbers versus time (Figure 5.7) has an interesting shape. The initial lag period in which the seedlings that germinated in the first fires mature is evident. After the second round of fires, many of the original invaded cells will be reaching saturation. Densification continues rapidly in the newly invaded cells and thus the scenarios with the larger invaded areas begin to steam ahead.

5.3 SPATIAL HETEROGENEITY

A landscape fragmented by rivers, firebreaks and topography will be likely to consist of a number of patches of vegetation that differ in age. Three scenarios were compared in order to establish the effect that differing degrees of spatial heterogeneity, in the form of different vegetation ages, has on the spread rate. Figures 5.5D-F show how the fire and vegetation zones were divided in order to provide different levels of heterogeneity. The first scenario consisted of a single fire zone, which meant that a fire would burn the entire modelling area. The second and third scenarios consisted of four and eight fire zones respectively. The vegetation layers were also divided into zones of differing vegetation ages in order to provide a heterogeneous starting point. The model was run 100 times for a period of one hundred years for each scenario. The results presented in Figures 5.8 and 5.9 represent the mean values of the 100 runs.

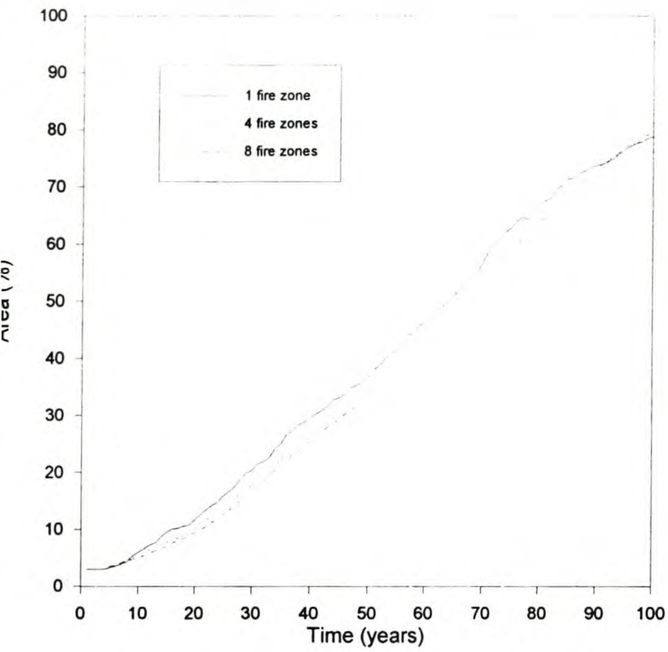


Figure 5.8:
Graph showing effect of spatial heterogeneity on the rate at which the invaded area increases.

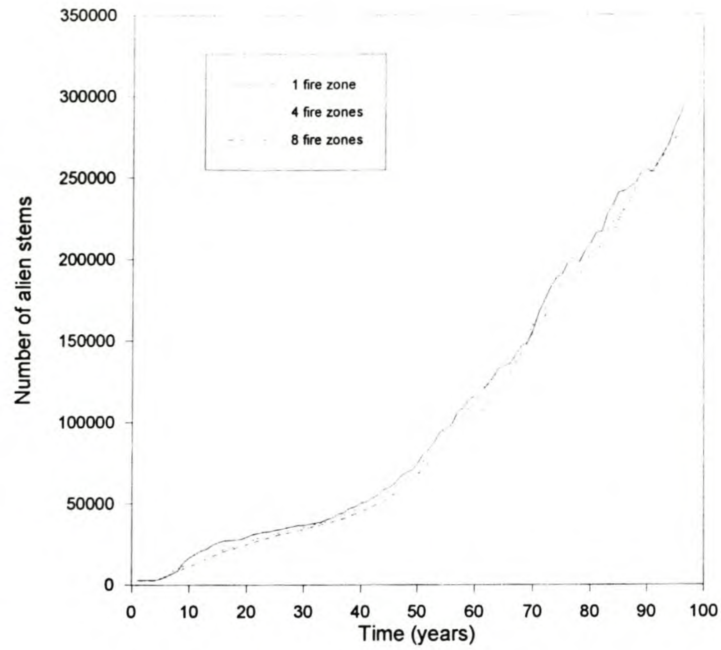


Figure 5.9:
Graph showing effect of spatial heterogeneity on the rate at which pine trees increase in number.

Figures 5.8 and 5.9 indicate that the number of fire zones has no influence on the mean invasion rate, with the only noticeable affect being that the curve for the single fire zone is less smooth than the other curves. Examining the standard deviations provides insight into how the number of fire zones influences the consistency of the model's predictions. As can be seen from Table 5.2, the standard deviation for the single fire zone scenario is much larger than that of the more fragmented scenarios. A phenomenon that is observable in this table, and is consistent to all the scenarios run throughout this study, is that the standard deviation increases with time. This is due to the continuous unfolding of different fire histories. The standard deviations appear to be large, however, the agreement of the means in many of the scenarios indicate that 100 runs was a satisfactory number to eliminate the stochastic element from the comparisons of the means.

Table 5.2: Standard deviations from the mean for three heterogeneity scenarios.

Scenario	Standard deviation			
	Area (%)		Number of stems	
	50 years	100 years	50 years	100 years
1 fire zone	8	12	34000	173000
4 fire zones	4	5	14000	77000
8 fire zones	2	4	9000	53000

Although the number of fire zones had little effect on the overall rate of spread or population increase, it was thought that it might influence the effectiveness of a clearing programme. In order to test this supposition, a series of tests involving the same three scenarios (Figures 5.5D-F) was carried out. Four different clearing strategies that prioritised juvenile, adult, sparse and dense alien vegetation in turn were tested. The model was run 50 times for each strategy, for each of the scenarios. The results presented in Table 5.3 show a definite influence of the selected strategy on clearing costs. The effect is particularly noticeable in the less effective strategies as these are implemented over a longer time and are therefore more susceptible to disruptions. Overall, the increase in the number of fire zones meant that there was a greater spread of plant ages and densities. The sparse and juvenile strategies could therefore be more focussed and consequently be more successful. The adult and dense strategies could also be more focussed, resulting in the ineffectiveness of these approaches being more pronounced.

Table 5.3: Cost of clearing strategies for different scenarios.

Scenario	Cost of clearing (kR/ha)			
	Juvenile	Adult	Sparse	Dense
1 fire zone	367	690	412	645
4 fire zones	330	474	389	440
8 fire zones	325	410	380	406

5.4 FIRE OCCURANCE

Fynbos ecosystems can benefit greatly under certain fire conditions and an ideal fire recurrence interval distribution (here referred to as *desired fire conditions*) has been calculated (Richardson, Van Wilgen, Le Maitre, Higgins & Forsyth 1994). Le Maitre (1998) calculated the parameters b and c of the hazard of burning function described in Section 4.2.2 for several areas, as well as for the hypothetical desired fire conditions. These parameters are presented in Table 5.4, while the cumulative fire distribution curves associated with the parameters are presented in Figure 4.2. The model was run 100 times for each of the sets of parameters in order to determine how sensitive the model was to different fire occurrence patterns.

Table 5.4: Hazard function parameters and mean fire intervals for the scenarios.

Scenario	b	c	Mean fire interval
Swartboskloof fire conditions	0.047	2.99	19 years
Cederberg fire conditions	0.063	1.77	14 years
Kammanassie fire conditions	0.086	2.35	10 years
Desired fire conditions	0.064	5.3	14 years

The results presented in Figures 5.10 and 5.11 indicate that the model is not particularly sensitive to changes in fire regime. However, the results of the Kammanassie scenario deviate interestingly from the other results. Due to the four-year initial fire free period included in the model, many of the original pine trees were able to reach ages that allowed them to survive fires. The higher fire frequency of the Kammanassie fire regime initially resulted in a more rapid densification. Few of the new seedlings in the Kammanassie scenario were able to reach a fire resistant age and therefore we see evidence of an unstable population in Figure 5.11 and a decrease in the area invasion rate shown in Figure 5.10. In the scenarios with lower fire frequencies a larger proportion of trees were able to reach fire resistant ages, resulting in more stable populations and steady invasion.

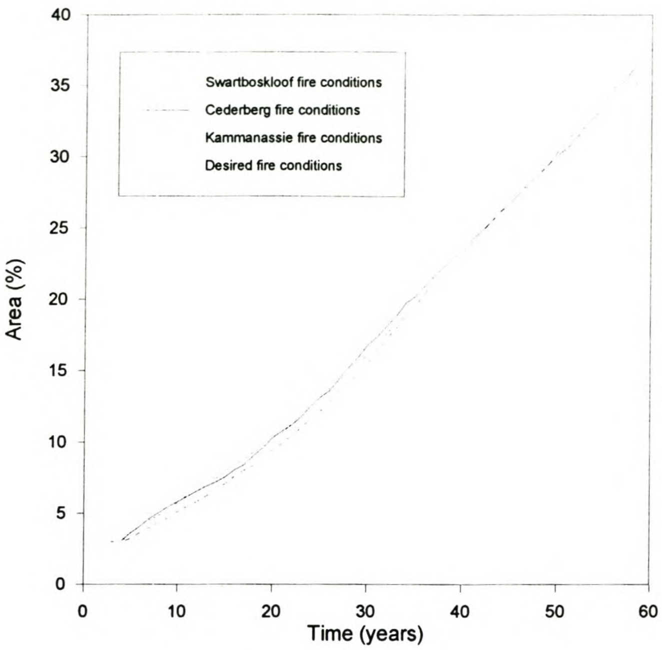


Figure 5.10:
Graph showing effect of different fire occurrence distributions on the rate at which the invaded area increases.

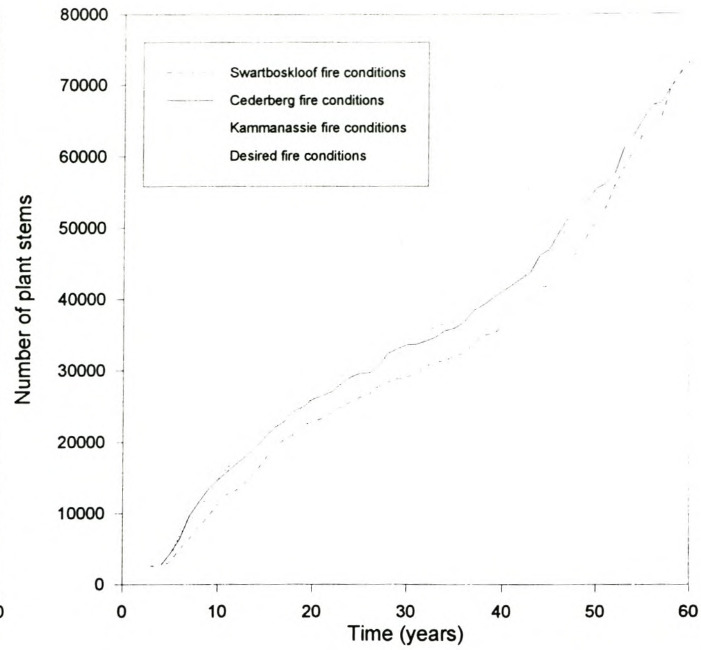


Figure 5.11:
Graph showing effect of different fire occurrence distributions on the rate at which pine trees increase in number.

CHAPTER 6:
INTEGRATION OF MODEL INTO ARCVIEW ENVIRONMENT

A variety of organizations are involved in funding, formulating and implementing clearing strategies. These range from national leaders to ecological experts, catchment managers and team supervisors. The more accessible the model is, the more people stand to benefit. The following points summarise what is needed to make the model more accessible:

- A user friendly interface;
- Realistic input data requirements;
- Simple, flexible and convenient data preparation; and
- Simple, flexible and convenient reporting.

As the ArcView platform is the accepted standard for catchment management in South Africa, it is believed that the model will be more accessible to decision makers if it is integrated into the ArcView environment. This will avoid problems associated with data importing and exporting.

6.1 DATA AVAILABILITY

A fair amount of alien vegetation mapping has recently taken place in the Western Cape. Many of the data sets are still under construction and thus the lack of readily available data is disappointing. The alien vegetation data sets of some catchments are extremely complex, with a wide variety of overlapping species. For the purposes of this preliminary evaluation of the model it was felt that simple sample datasets would suffice to illustrate the broad principles under investigation.

6.2 DATA PREPARATION

Users such as catchment managers will need to change the input data layers and clearing strategy parameters in order to simulate the spread of alien vegetation in different areas. They may also wish to edit the alien vegetation data layers in order to simulate hypothetical scenarios. An Avenue extension has been developed to facilitate the creation of the GIS data layers required by the model. The extension adds a dropdown menu to the top bar of the view, as shown in Figure 6.1.

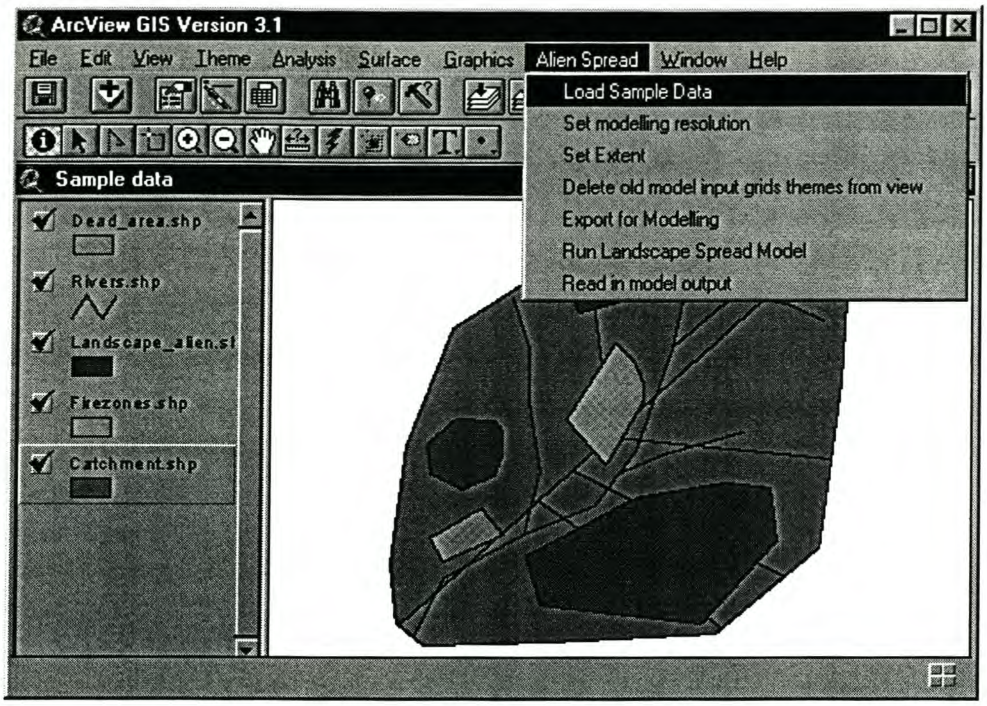


Figure 6.1: The ArcView extension in use.

Working from the top of the menu to the bottom the user is able to:

Load sample data – A sample data set is provided so that the user can see the format their data needs to be in. The user has to change the names of their themes through the theme properties menu, to match those in the sample data set. They must edit the tables associated with the themes to have the required fields in the correct units.

Set modelling resolution – The cell size to be used when creating the grid layers is entered though this menu.

Set extent – The user must draw and select a rectangle of the desired extent before selecting this option. The extents of the rectangle will be calculated to the nearest multiple of the chosen resolution. These extents are then used as the extents for the various grid layers.

Delete old model input grid themes from view – Several grid layers are added to the view for the user to check after the data is exported. This option has been included as an easy way to clean up the view before re-exporting the data.

Export for modelling - The laborious process of converting each shape file into a grid and then into ASCII format is automated for the user by selecting this option. This option also warns the user about any inconsistencies or omitted data.

Run landscape spread model – This is a short cut to the Clear model, which can also be accessed by running the executable file through Windows Explorer or via an icon on the desktop.

Read in model output - This routine provides a convenient way to import the ASCII files outputted by the model into grid format and into the active view.

6.3 CHANGES TO THE CLEAR MODEL INTERFACE

The interface of the Clear model has been described in detail in Section 4.4. This section serves to highlight the changes that took place as part of this study. The original model interface was developed by Steve Higgins to meet the needs of ecological experts. This requires an in depth knowledge of a particular species spread pattern and the internal workings of the model, in order to enter the large number of coefficients and parameters required. If parameters are misunderstood, the simulations will be invalid and will result in mistrust in the model or erroneous decisions.

The original menus have undergone minor modifications in terms of layout and labelling to avoid misunderstanding. However, it is still advisable that users make use of the ability to upload parameter files that have been drawn up by ecological experts. This means they need only alter the parameters they clearly understand. Refinements made to the parameters can be saved to a parameter file for convenient re-use. Menus for controlling the input and output of spatial data, as well as budget files and batch files for multiple runs have been added. Although the menus have been documented as far as possible in this report, the interface could still benefit greatly from help screens for each menu.

6.4 REPORTING

Producing spatial results in the form of grids that can be processed and viewed in ArcView allows the user to analyse the information with existing tools and compare the results to existing datasets. Examples of possible types of analysis include calculating the threat to valuable areas of natural vegetation and the impact on water usage.

Due to the stochastic nature of many of the model processes, a modeller will often want to run a large number of runs in order to assess the range of possible outcomes. Therefore, the model allows for batches of runs to be modelled automatically. The output of these batch runs is written into two text files. The first of which is a summary of the total amount spent and number of years until the alien plants were eradicated for each run in the batch. The second file provides a yearly account of alien plant numbers as well as the area invaded and burnt for each run. These files are particularly useful as they can be loaded into any spreadsheet package and used for analysing the success of different clearing strategies or accessing the effects of changing various parameters.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

The two key questions this thesis set out to address were whether the Clear model would be suitable for wider use and whether it could be readily applied when modelling areas differing in spatial characteristics. The findings with respect to these enquiries are discussed below.

7.1 SUITABILITY FOR WIDER IMPLEMENTATION

In this study the Clear model was shown to be a useful tool for evaluating clearing strategies and exploring various aspects of alien plant invasions. Although decision support tools are purported to be essential for environmental management, there are relatively few examples where such systems are successfully integrated into decision-making processes on an ongoing basis. This is due to some common problems with many decision support tools, in particular:

- Inflexibility;
- Unnecessary complexity;
- Lack of integration with existing tools; and
- Not fully meeting the needs of the people who are expected to use them.

In the following section the strengths and weakness of the Clear model are summarised for each of these aspects.

7.1.1 Flexibility

The way in which environmental decisions are made is continually changing. Therefore, tools that attempt to make decisions for managers are quickly outdated. Tools that allow managers to pose a number of questions and provide them with a better understanding of their environment are more likely to enjoy extended use. The Clear model is extremely flexible and can answer a wide range of questions. Unfortunately this is at the expense of simplicity. Although the model can provide a relative costing of various clearing strategies, the current simplified costing routines do not provide an accurate budgeting tool. Further investigation is needed in order to establish how best to incorporate the added levels of complexity needed to provide a more flexible and accurate budgeting facility.

7.1.2 Complexity

Tools that try to answer too many questions at varying scales can quickly become complex and confusing. The Clear model is definitely guilty of this. For research purposes it is convenient to be able to investigate all aspects of alien spread using a single tool. However, no manager will have the time or inclination to use all the functionality included in the model. It is therefore recommended that managers be interviewed in order to establish which features of the model are most useful to them. The superfluous features can then be hidden from the users, resulting in a less baffling interface. The SELES model for the Cape Peninsula is a good example of simplifying the interface to allow a limited range of questions to be answered.

A different set of features may be more appropriate for education purposes. Once again, the model interface can be scaled down to allow learners to focus on a subset of parameters. Unfortunately, the current way in which variables are exchanged between the interfaces and various components of the code will make this difficult to do. If the code were rewritten following a more object-orientated approach this sort of customisation would be far easier.

The large number of input parameters may be difficult for even an expert to provide. A number of these parameters will need to be estimated as the literature provides limited information on the life history of some plant species and experiments are not always practical or possible. Furthermore, the local fire history (an important driving force in the model) may be unknown and/or difficult to predict.

As a consequence of these uncertainties, the number of "expert guesses" required to parametize the model could lead to a manifestation of the adage "garbage in, garbage out". It is therefore imperative that the inputs are provided by experts in a responsible, defensible way. Non-expert users should obtain complete parameter files from reliable experts and they should be made aware of the spatial scales at which the parameters will no longer be valid.

7.1.3 Integration with existing tools

Many South African researchers and students in the environmental and ecological fields have direct or indirect access to ArcView software and will thus find it possible to use the ArcView extension. The WfW programme has accepted ArcView as a software standard and therefore it is believed that the ArcView extension developed in this study can easily be integrated into their current analysis environment. The

ArcView extension for processing the input and output data of the Clear model makes use of the Spatial Analyst extension for ArcView. It is a concern that the cost of acquiring this additional piece of software will limit the extent to which the ArcView extension developed for the Clear model will be used.

7.1.4 Meeting real needs

The three main groups of people who could benefit from the use of the model are:

- Ecology students needing to familiarise themselves with the process of plant spread;
- Researchers investigating invasion processes; and
- Managers who need to make decisions about which clearing strategies to adopt.

The extent to which these needs can be met by the Clear model is discussed below.

(a) Meeting the needs of ecology students

In the absence of a dynamic spatial model such as Clear, the processes involved in an invasion could only be described in terms of complex mathematical equations. Even if a student had the mathematical ability to understand these equations, it remained impossible for them to gain an overview of an invasion. This is due to the numerous dynamic and spatial interactions between the processes that can only be calculated by computer. Allowing learners to alter parameters for a process and then view the animated visual display, provides them with an intuitive understanding of how the process influences the overall invasion.

(b) Meeting the needs of researchers

The parameters used in this study are based on the limited amount of available empirical data that currently exists and in many cases are only educated guesses. As further empirical studies on various aspects of invasive plant histories and physiology are completed these parameters can be refined. Incorporating new findings into the Clear model will allow these findings to be evaluated in the context of the overall invasion process.

(c) Meeting the needs of managers

The Clear model is a useful decision support tool as it enables managers to:

- Estimate the cost of clearing and assess the effect of budget changes;
- Calculate the relative effectiveness of clearing strategies that prioritise juvenile, adult, sparse or dense plants;

- Calculate the relative effectiveness of clearing techniques such as mechanical clearing, bio-control or chemical treatment; and
- Predict the future impact of an invasion on the natural resources.

Unfortunately the stochastic nature of the model implies that the same parameters will seldom generate the same results. This may result in a lack of confidence in the model results. It needs to be emphasised that decisions should be taken by comparing mean values of a large number of runs, while taking the standard deviations into account. The standard deviation tells us whether the phenomenon observed will be repeated with any certainty. Although the *batch scenario form* (Figure 4.17) allows the user to automate the large number of runs required, the batch may take a few hours to complete and the outputs will have to be manipulated and examined. Due to the complicated and interrelated nature of the modelled processes, it is only by examining a number of carefully planned scenarios that conclusions can be made with any certainty. It is therefore a concern that managers searching for quick answers would find the model too time consuming to use properly. This problem could be addressed by having a researcher who is familiar with the model conduct the model runs, in order to answer the manager's questions more effectively.

7.2 SUITABILITY FOR USE IN AREAS DIFFERING IN SPATIAL CHARACTERISTICS

A series of tests were conducted in order to check the sensitivity of the model to spatial aspects of the area being modelled. These tests had several interesting results and the key findings are discussed below.

Firstly, the model was found to be sensitive to changes in resolution and it is therefore recommended that the model be reparameterised when used at different scales. This finding contradicts the initial finding by Higgins (1998). The wider range of resolutions tested here probably accounts for this discrepancy.

Secondly, the initial level of fragmentation of the alien invasion was shown to have a major influence on the invasion rate. Further empirical studies of invasion histories are required in order to verify the predicted differences in invasion rates. Gaining a better understanding of the relationship between initial fragmentation and spread rate will provide for more accurate budgeting and improved strategy selection.

Thirdly, it was found that the greater levels of spatial heterogeneity with respect to vegetation age did not significantly affect the spread rate. However, this did increase the effectiveness of clearing strategies that prioritised the clearing of juvenile or sparsely distributed plants.

Based on these tests, it can be concluded that the model can be readily applied to new areas, provided the influence of spatial characteristics is understood and accommodated. The model tests in this study focussed on *Pinus pinaster* and manual clearing techniques. The above findings are probably equally relevant to a number of other invasive species. For example, Higgins (1998) has also conducted model studies on *Acacia cyclops, Pinus radiata, Hakea spp* and *Acacia saligna.* Further investigations of these and other species will enhance our understanding of their invasion characteristics as well as build confidence in the model. The model is also capable of simulating a range of other clearing techniques and strategies. This model functionality should also be evaluated, as there is much we can learn by "trial and error" studies of different approaches to solving alien invasive plant problems in South Africa, as well as internationally.

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APPENDIX :

COMPACT DISC CONTAINING ARCVIEW EXTENSION AND CLEAR MODEL

A compact disc containing the ArcView extension and Clear model has been inserted into the copies of the thesis placed in the Stellenbosch Geography Library and the CSIR Documentation Centre. This compact disc also contains the SEIBS and SELES models as well as a number of spreadsheets that can assist one in parameterising the models. Please read the readme.doc file for further instructions.